ARCADIA

Advanced Readout CMOS Architectures with
Depleted Integrated sensor Arrays:

Test beam & LASER scan

IDEA Collaboration meeting – Bologna - 14/06/19

Istituto Nazionale di Fisica Nucleare

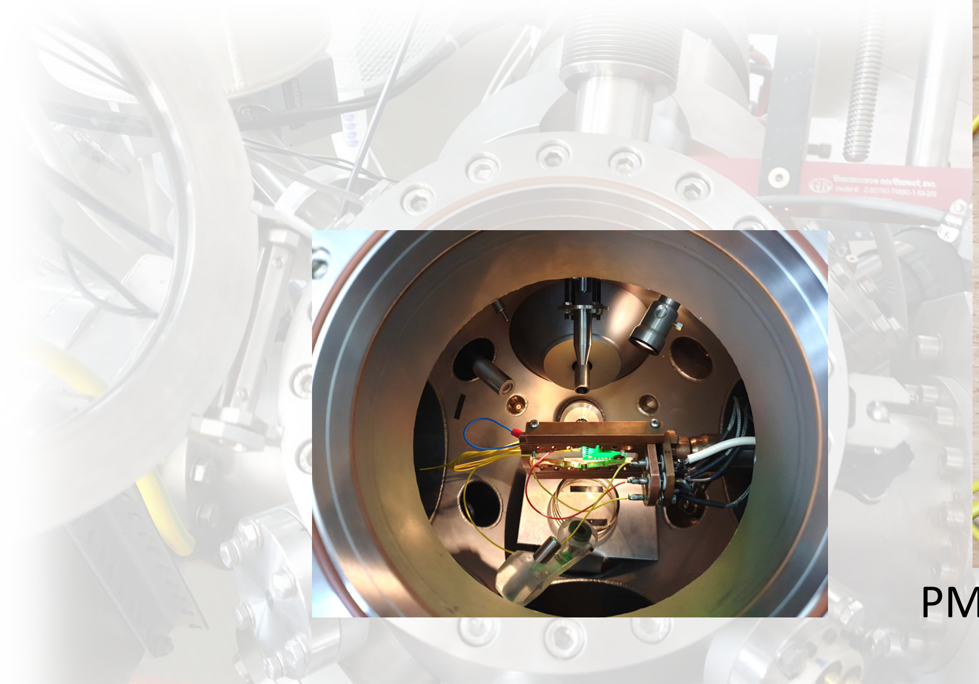
TO GIAMPAOLO Raffaele Aaron

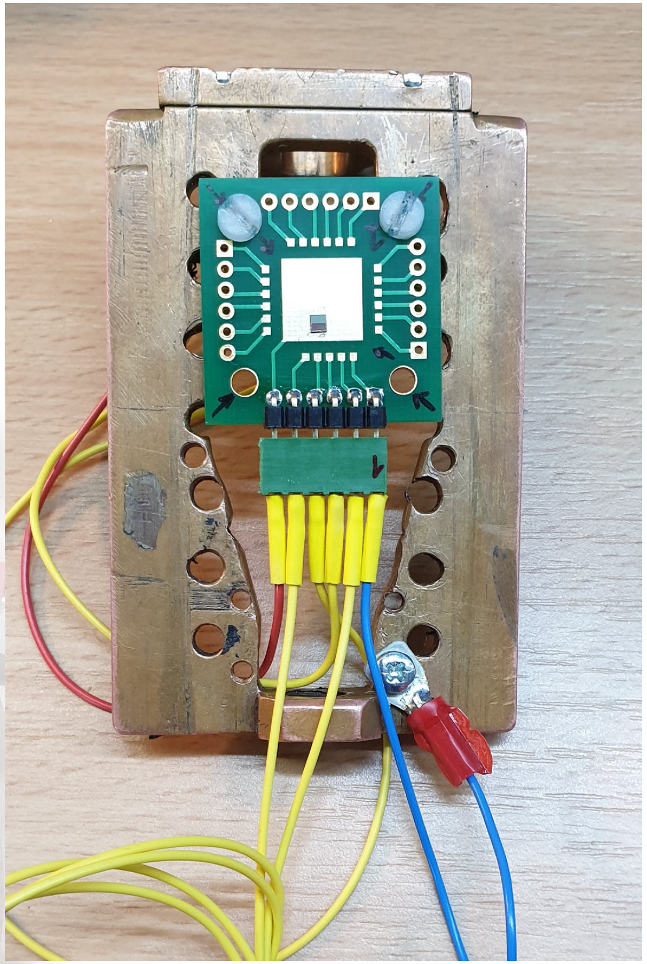
The institute is located in Zagreb, Croatia

- Employs ~1k researchers
- 600 keV to 2 MeV Tandetron (used for our tests)
- 1 to 6 MeV proton source using a TANDEM
- LASER TCT laboratory

CHARACTERIZATION OF SEED* SENSORS

- Test structures:
    - **Pseudo-Matrices** (PM)
    - Diodes
    - MOS-Capacitors
- A sensor embedded with readout electronics called MATISSE (Monolithic AcTIve pixel SenSor Electronics)
- Each structure has been produced with ***3 different thicknesses*** *100, 300 and 400* µm





PM mounted on beam sample holder.

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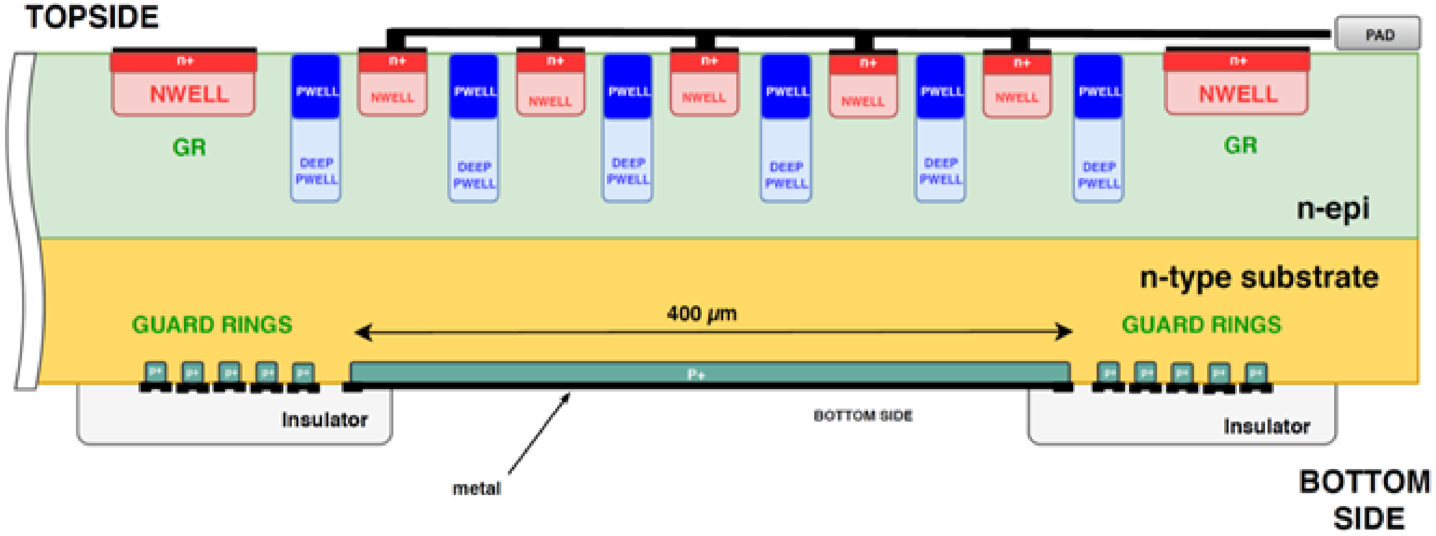
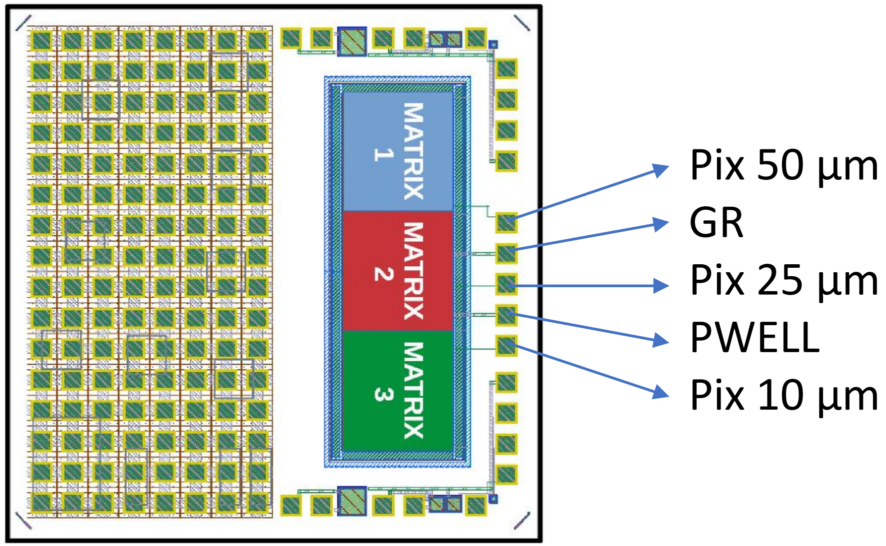
* Sensor with Embedded Electronics Development

PSEUDO MATRICES

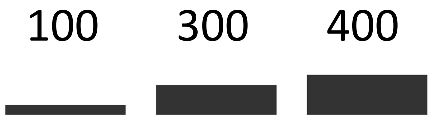
Pseudo-matrices (PM)





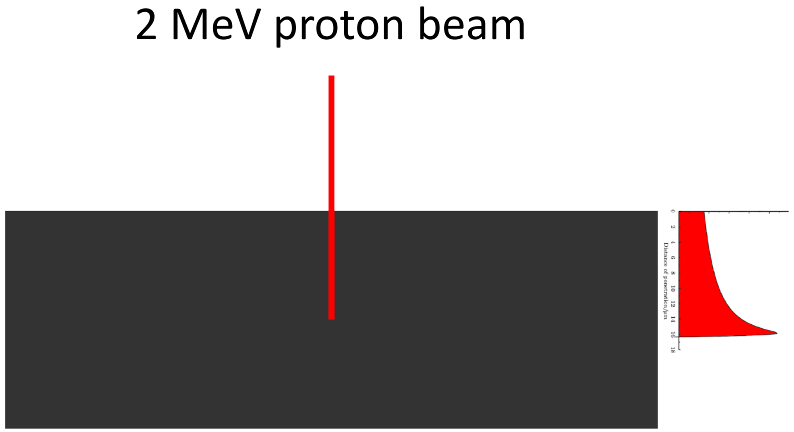
- ○ Three different ***thicknesses***: 100 µm, 300 µm and 400 µm
- ○ Three matrices with different ***pixel sizes***: 10 µm (40 x 45), 25 µm (16 x 18) and 50 µm (8 x 9)
- ○ On the top side, the ***deep-pwell*** is built, required to implement the CMOS electronics (no electronics on PM)
- ○ All the collector nodes of a matrix are ***shorted*** and connected to a PAD (Top right image, bonded on carrier PCB)
- ○ Each pixel is shorted using ***Al metal lines*** of increasing width per PM: 6, 8 and 15 µm

PSEUDO MATRICES RECAP GOAL

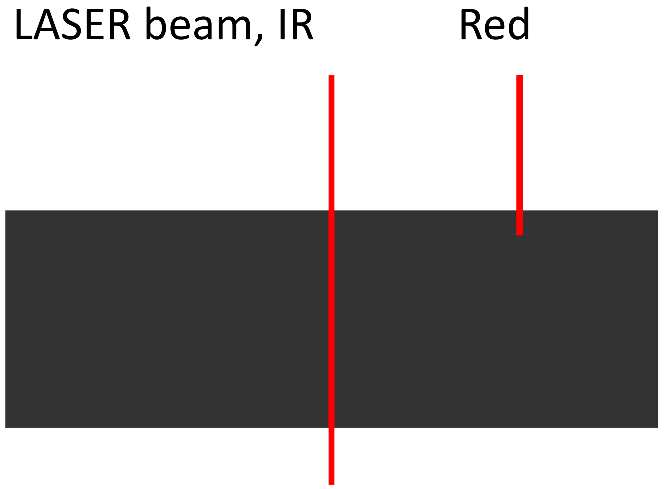


3 Thicknesses [µm]

3 Pixel Pitches [µm]

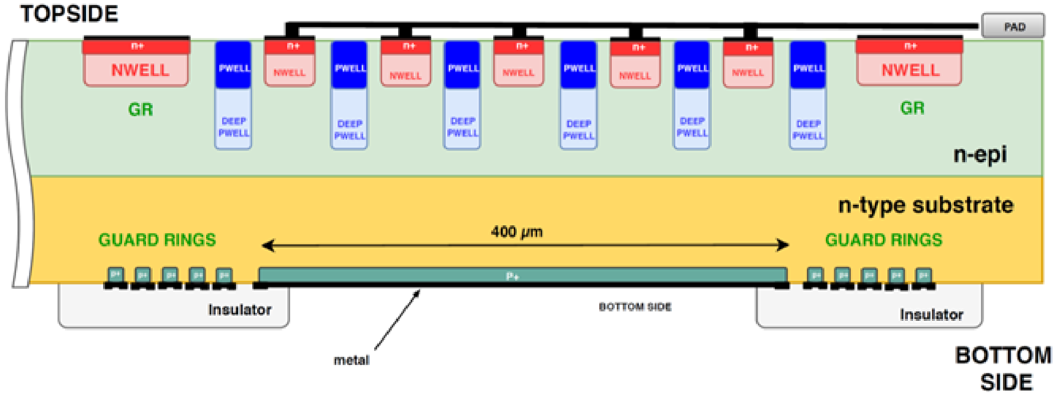


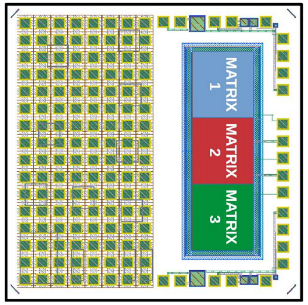
Bragg Peak ⇒ full energy deposition within 60 µm of Si



Continuous almost constant LET, similar to *mip*

GOAL

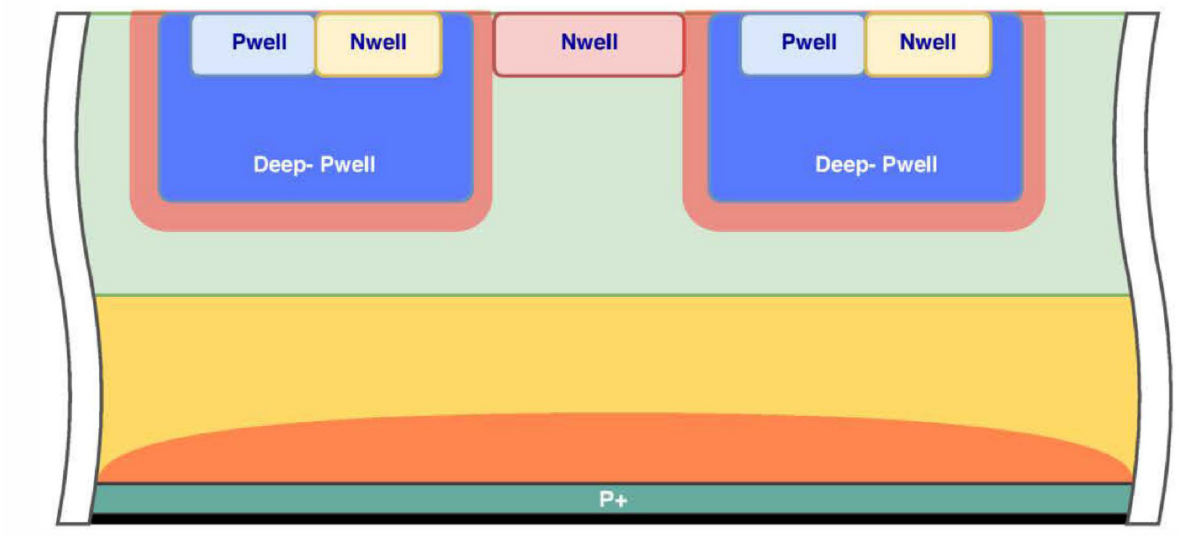




Using a 2 MeV proton source:

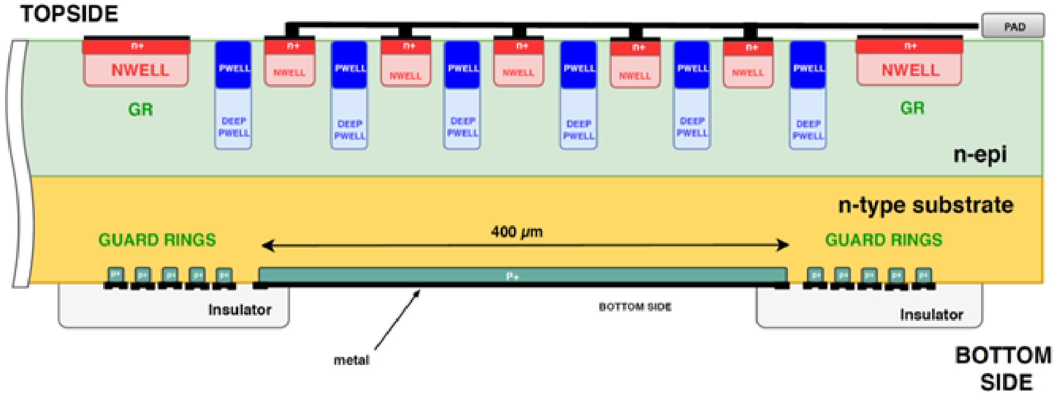
- ○ Test all thicknesses
- ○ Test all PM Pixel pitches

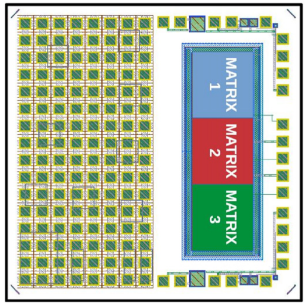
$$V_{HV} = 0\ V$$

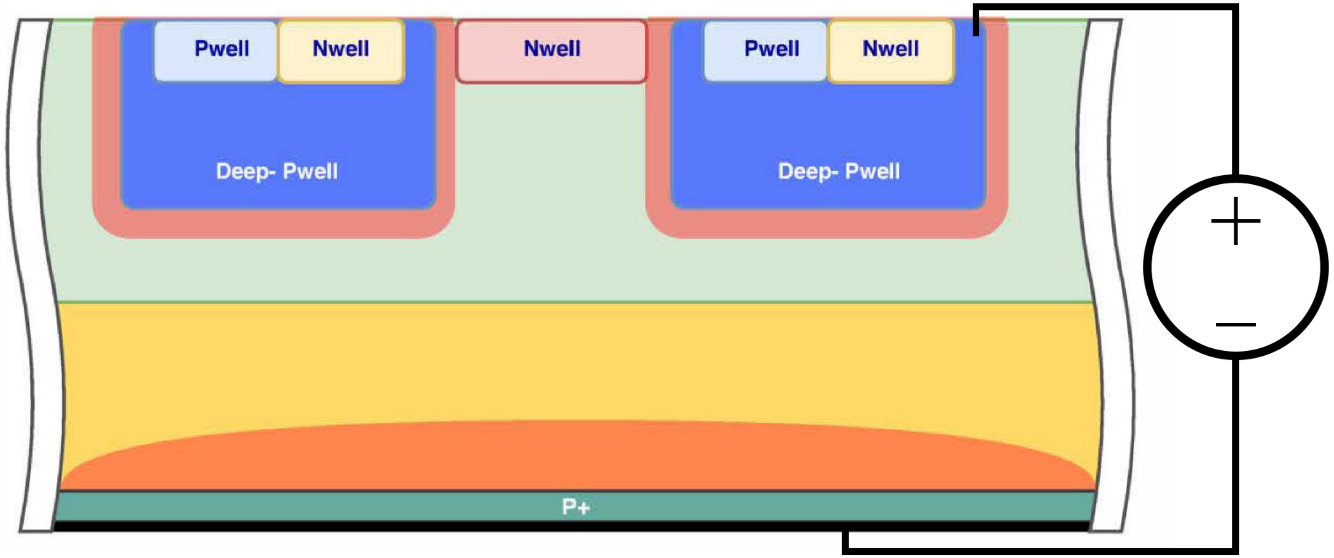


Thickness [μm]	V_{fd}
100	50
300	150
400	200

GOAL







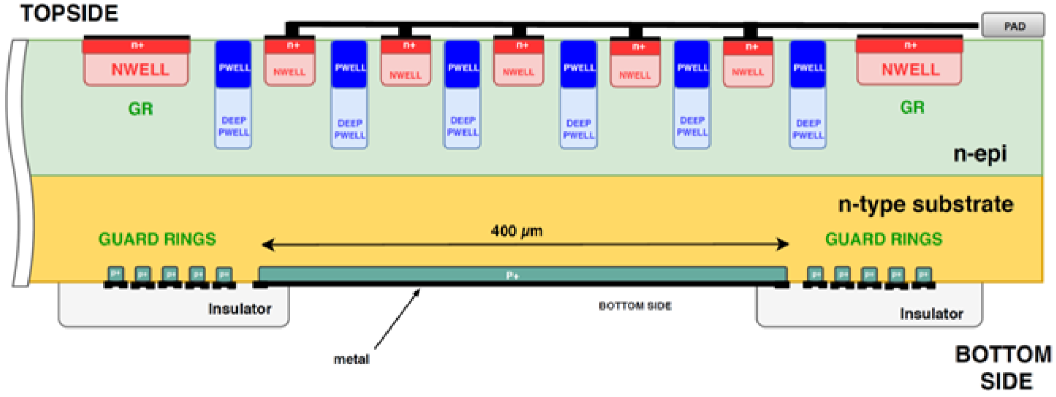
Using a 2 MeV proton source:
- ○ Test all thicknesses
- ○ Test all PM Pixel pitches

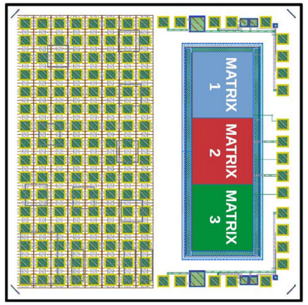
$$V_{HV} = 0\ V$$

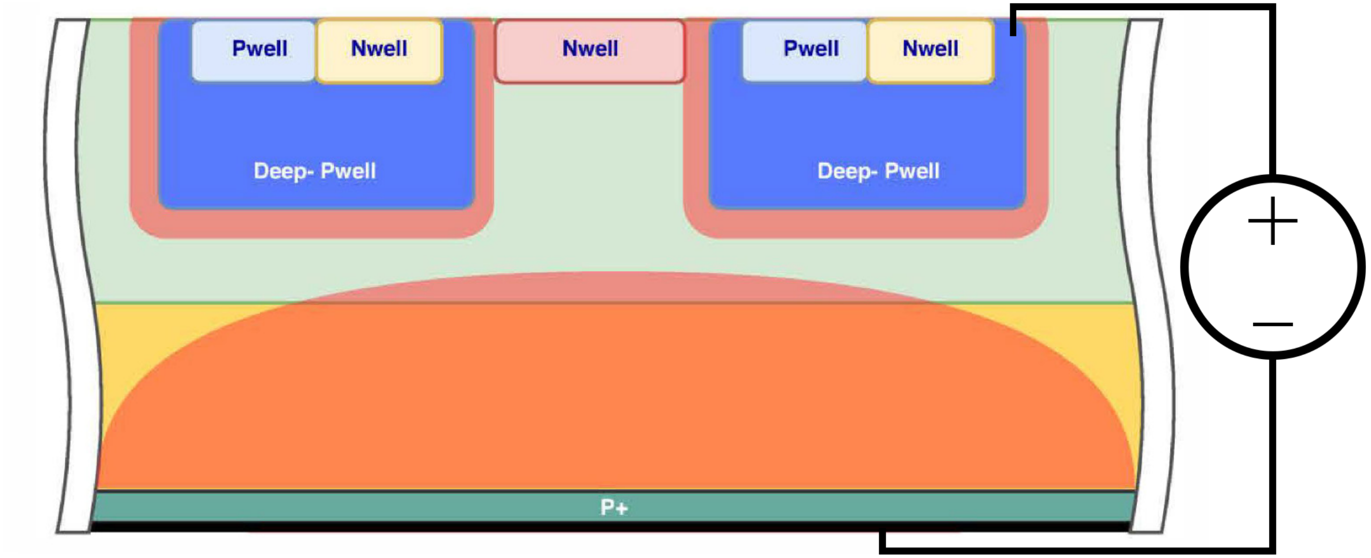
1. Reach the ***full depletion voltage,*** V_{fd}

Thickness [μm]	V_{fd}
100	50
300	150
400	200

GOAL







Using a 2 MeV proton source:

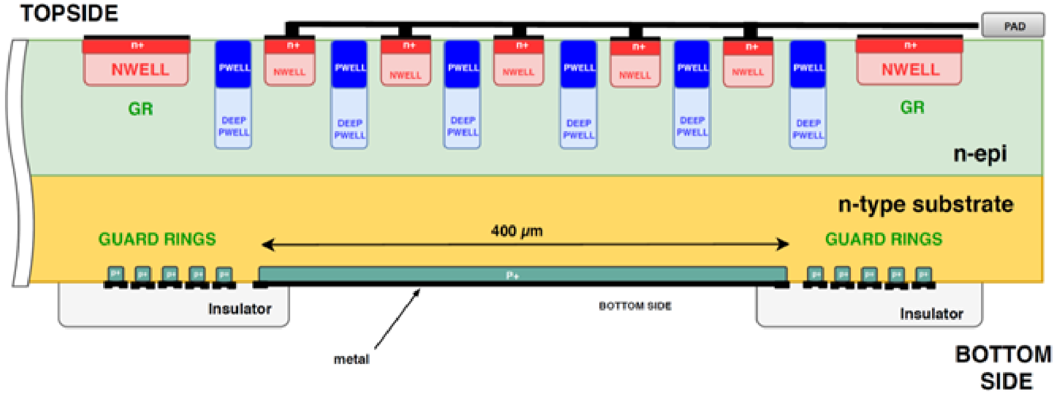
- ○ Test all thicknesses
- ○ Test all PM Pixel pitches

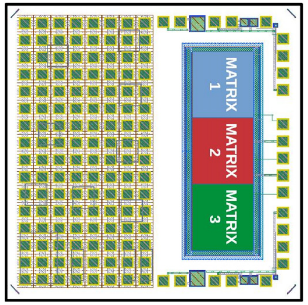
$$V_{HV} = 0\,V \rightarrow 50\,V$$

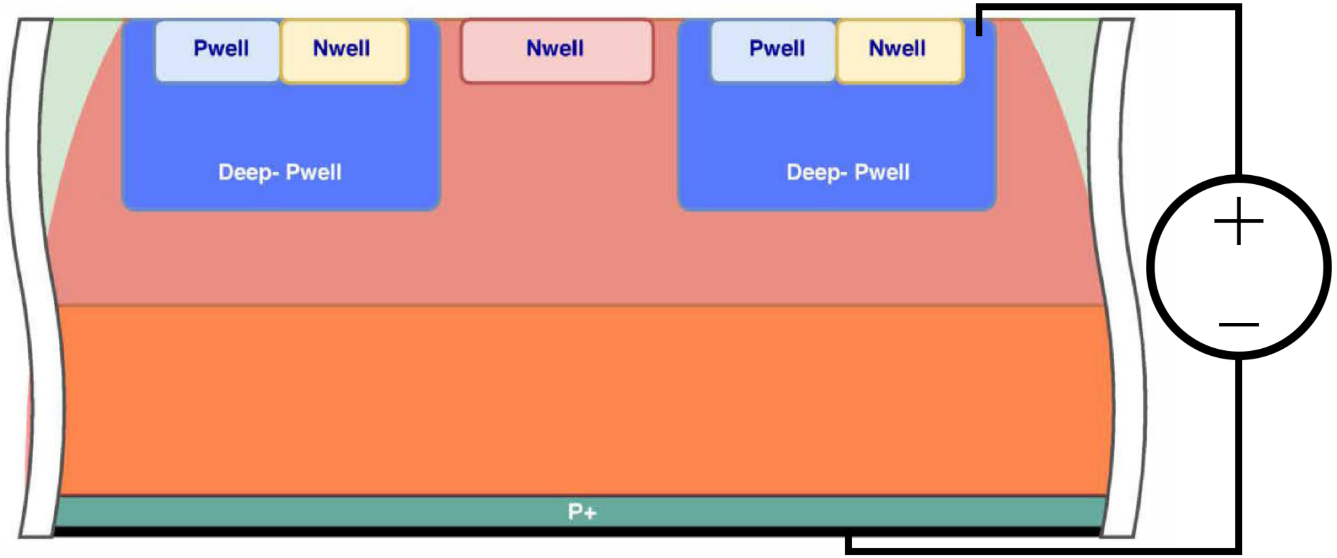
1. Reach the ***full depletion voltage,*** V_{fd}

Thickness [μm]	V_{fd}
100	50
300	150
400	200

GOAL







Using a 2 MeV proton source:

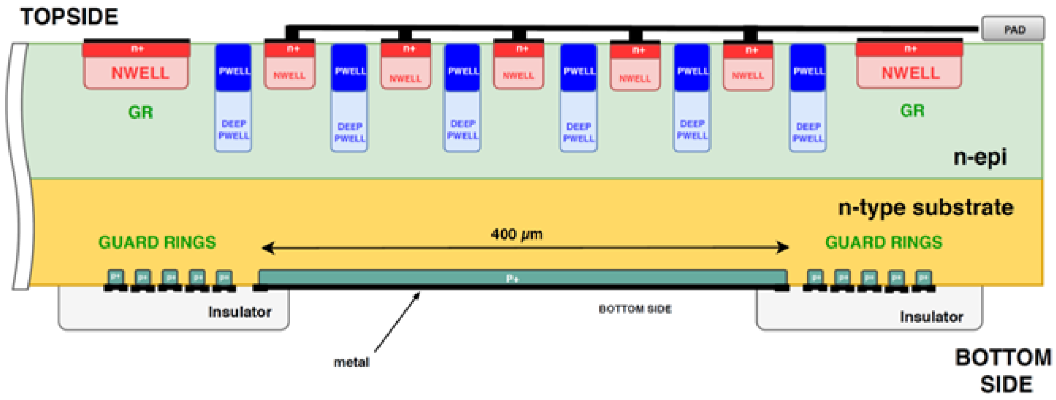
- ○ Test all thicknesses
- ○ Test all PM Pixel pitches

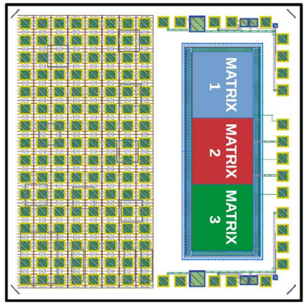
$$V_{HV} = 0\,V \rightarrow 50\,V \rightarrow 180\,V$$

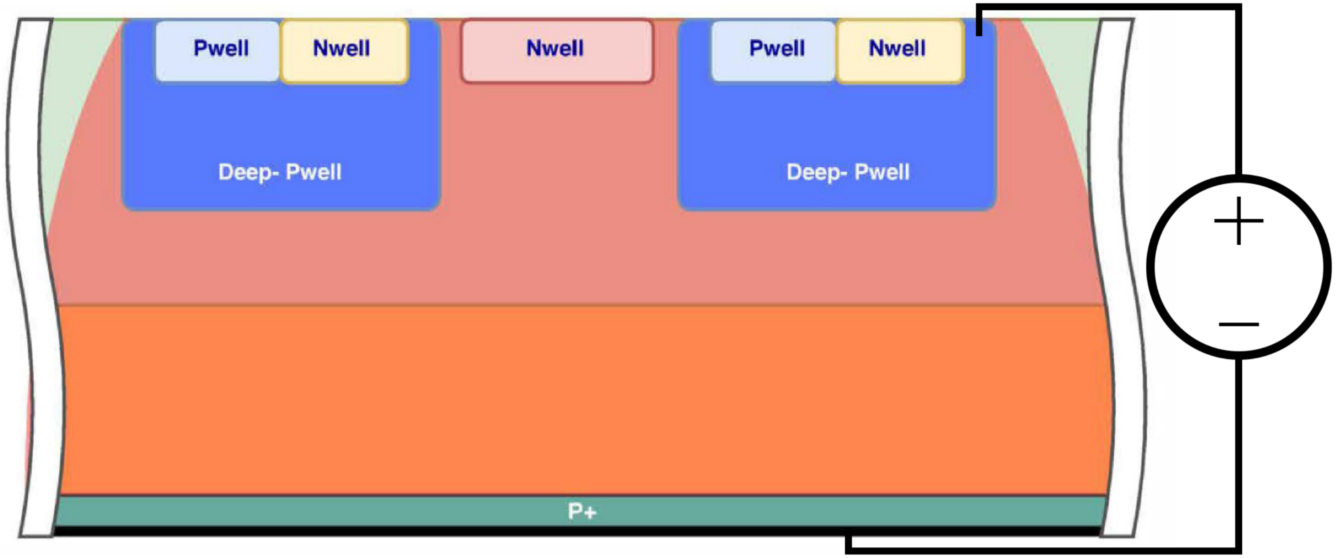
1. Reach the ***full depletion voltage,*** V_{fd}

Thickness [μm]	V_{fd}
100	50
300	150
400	200

GOAL







Using a 2 MeV proton source:

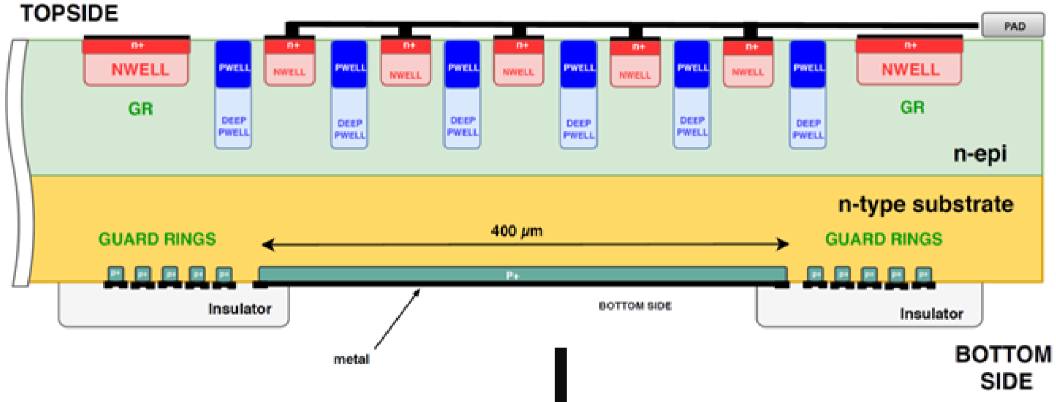
- ○ Test all thicknesses
- ○ Test all PM Pixel pitches

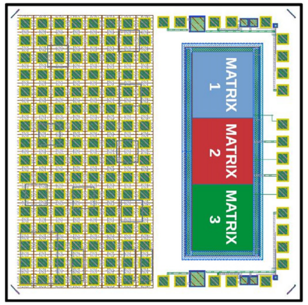
$$V_{HV} = 0\,V \to 50\,V \to 180\,V$$

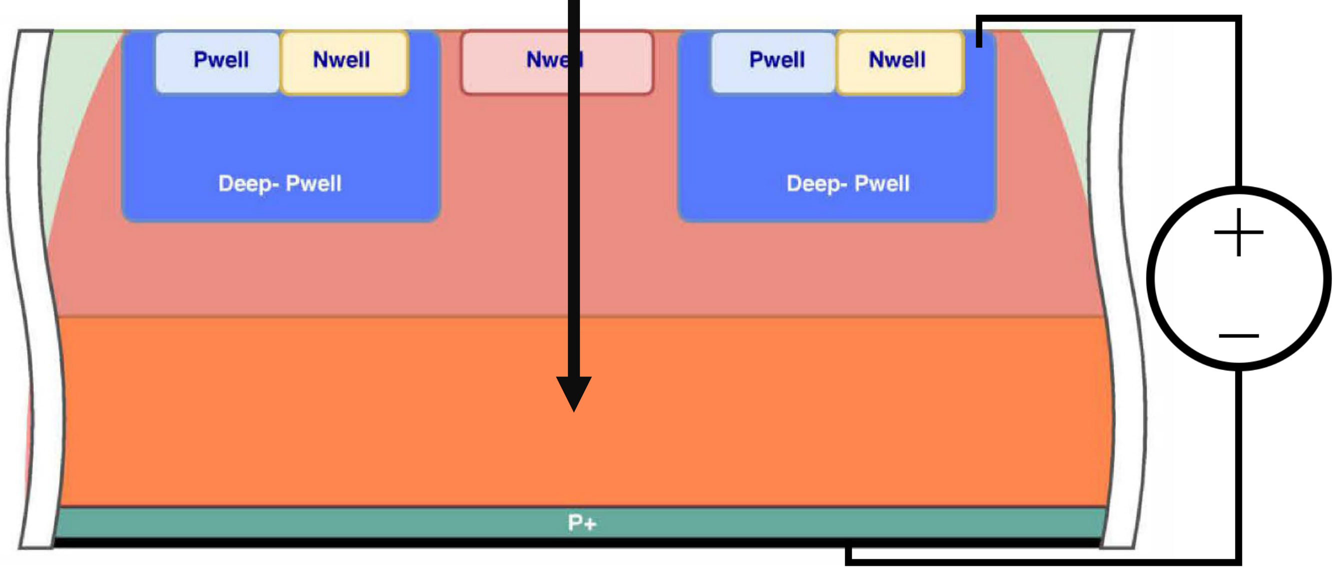
1. Reach the ***full depletion voltage,*** V_{fd}
2. Hit the PM with ***2 MeV protons***

Thickness [µm]	V_{fd}
100	50
300	150
400	200

GOAL







Using a 2 MeV proton source:

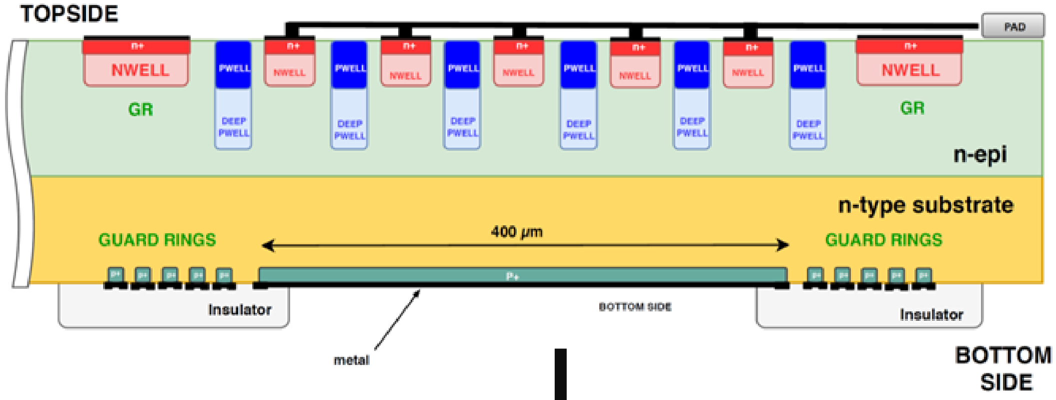
- ○ Test all thicknesses
- ○ Test all PM Pixel pitches

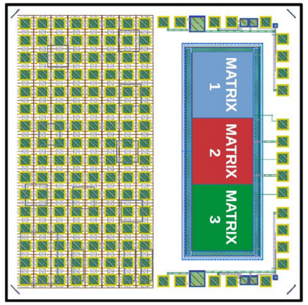
$$V_{HV} = 0\,V \rightarrow 50\,V \rightarrow 180\,V$$

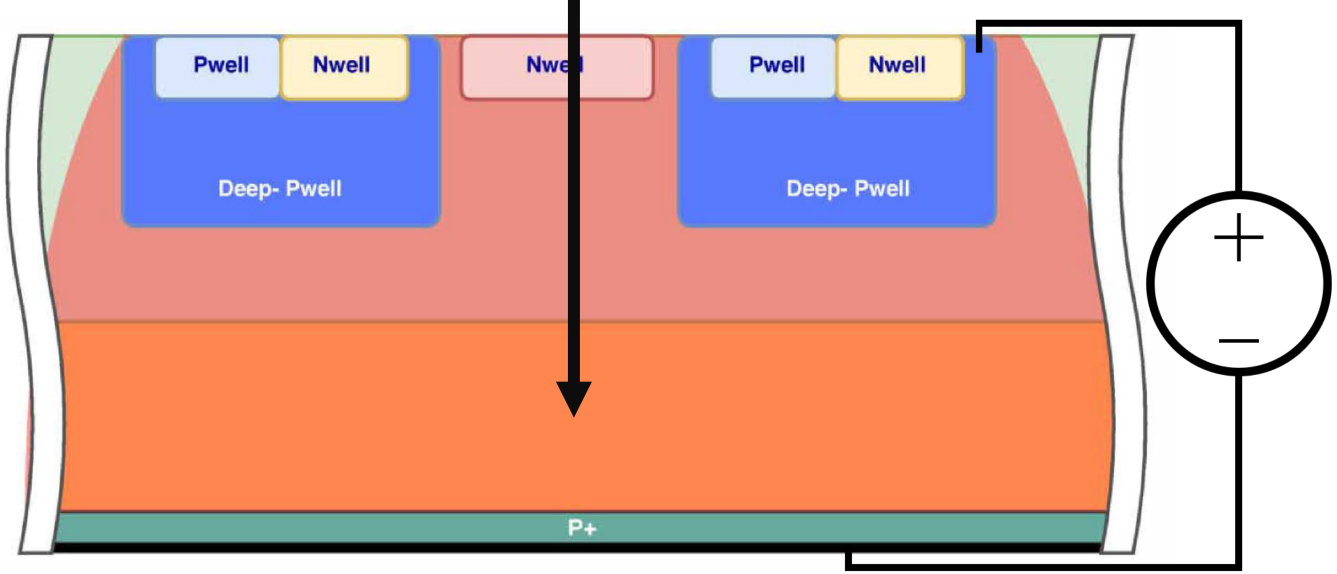
1. Reach the ***full depletion voltage***, V_{fd}
2. Hit the PM with ***2 MeV protons***
3. Scan the whole PM surface

Thickness [μm]	V_{fd}
100	50
300	150
400	200

GOAL







Using a 2 MeV proton source:

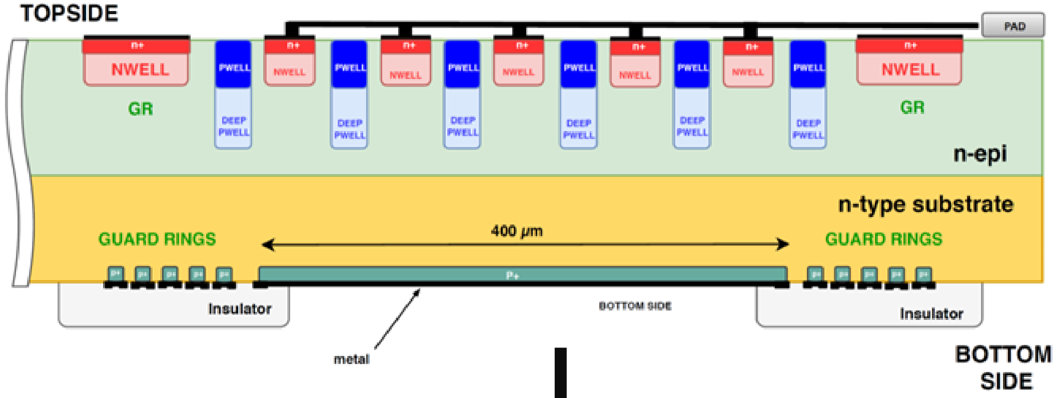
- ○ Test all thicknesses
- ○ Test all PM Pixel pitches

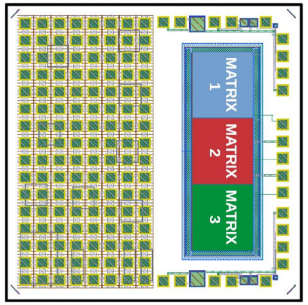
$$V_{HV} = 0\,V \rightarrow 50\,V \rightarrow 180\,V$$

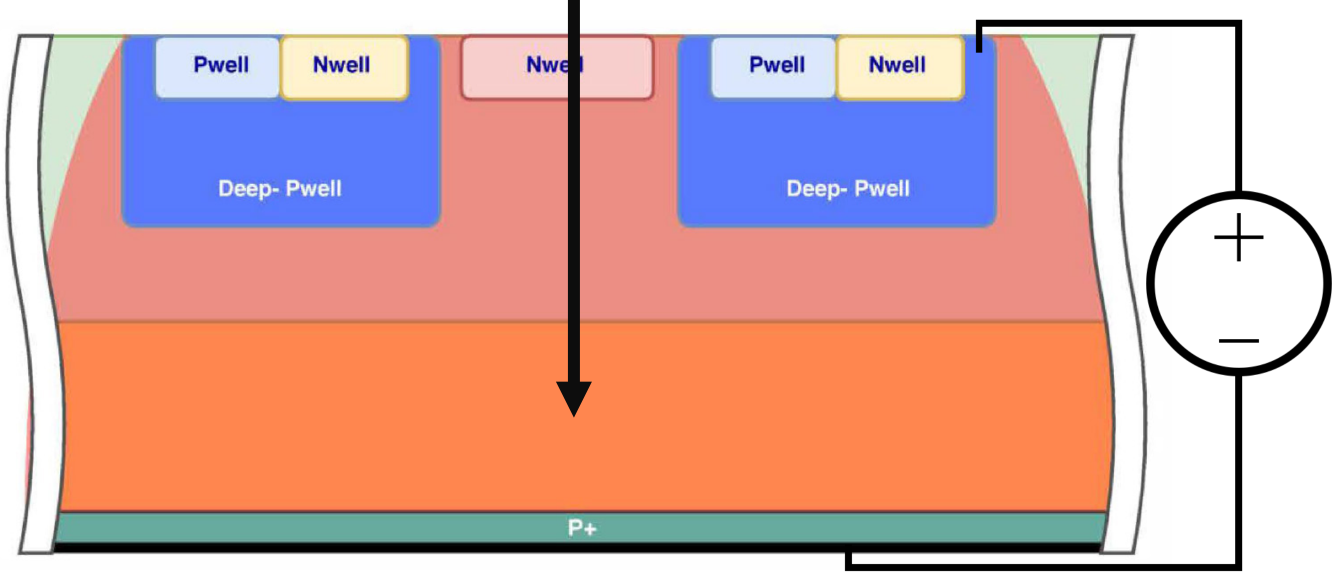
1. Reach the ***full depletion voltage***, V_{fd}
2. Hit the PM with ***2 MeV protons***
3. Scan the whole PM surface
4. Generate maps of the interactions

Thickness [μm]	V_{fd}
100	50
300	150
400	200

GOAL







Using a 2 MeV proton source:

- Test all thicknesses
- Test all PM Pixel pitches

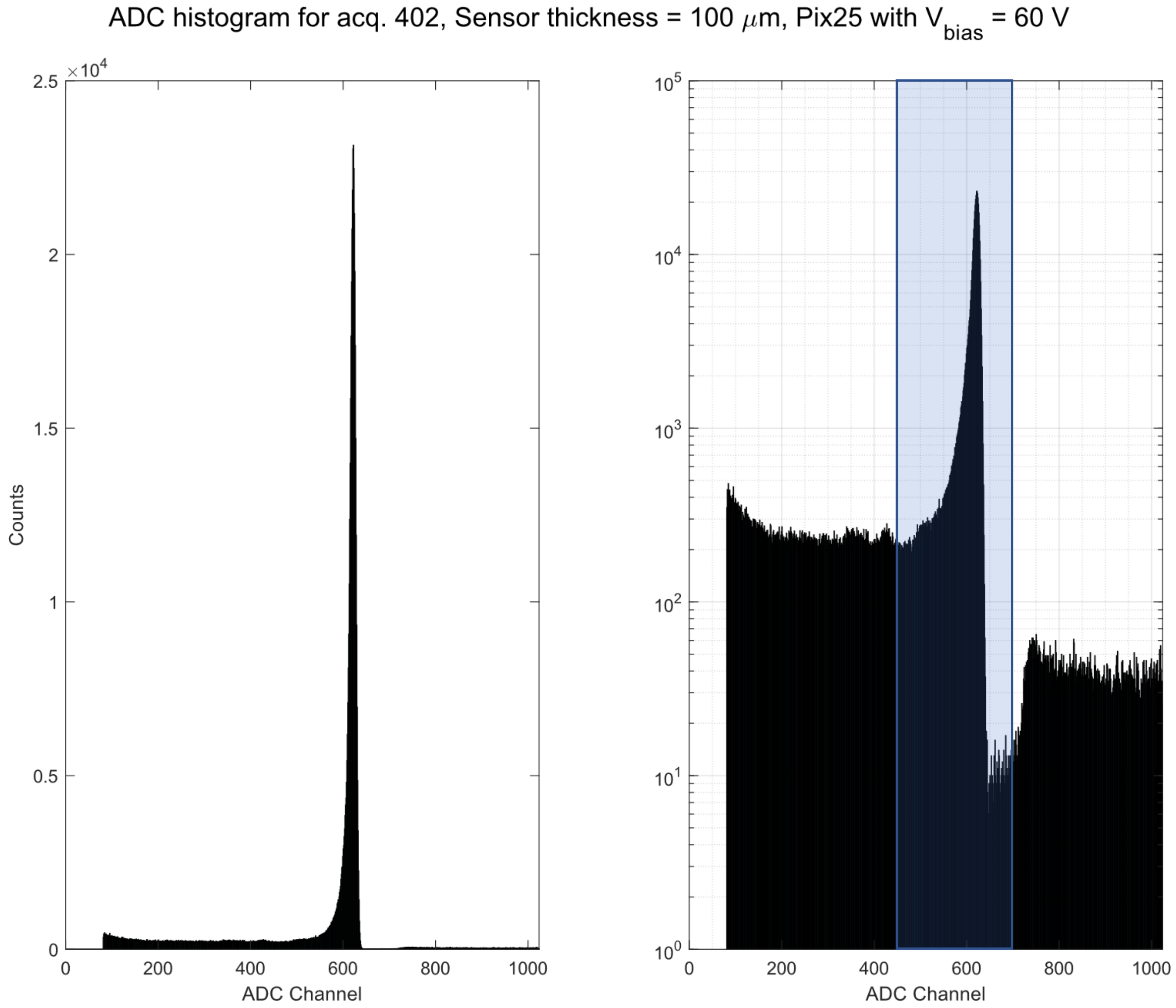
Extra test: TCT evaluation of 300 μm sensor

Biasing voltages:

- $V_{HV} = 150\ V$
- $V_{DC,pixel} = 1.2\ V$
- $V_{GR} = 1.2\ V$
- $V_{pwell} = 0\ V$

Thickness [μm]	V_{fd}
100	50
300	150
400	200

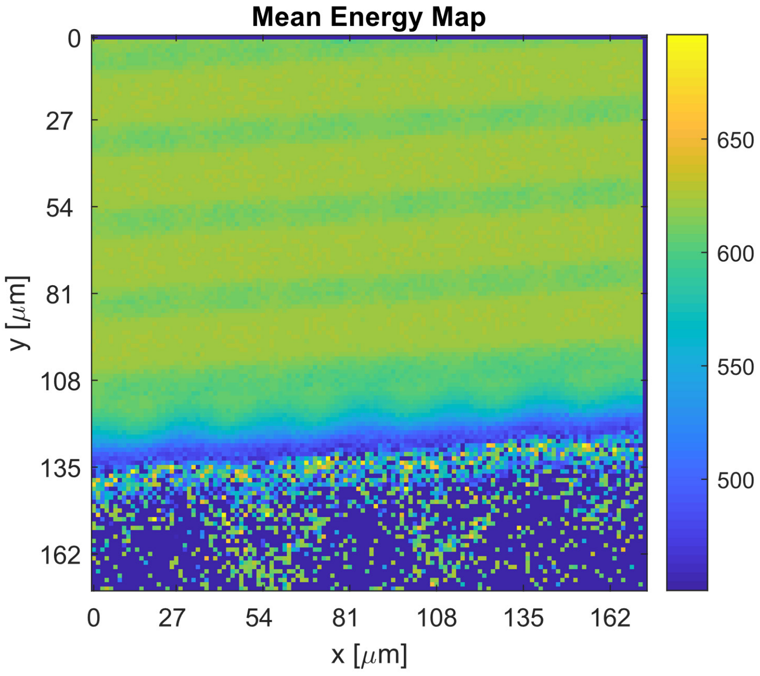
SCAN STUDY

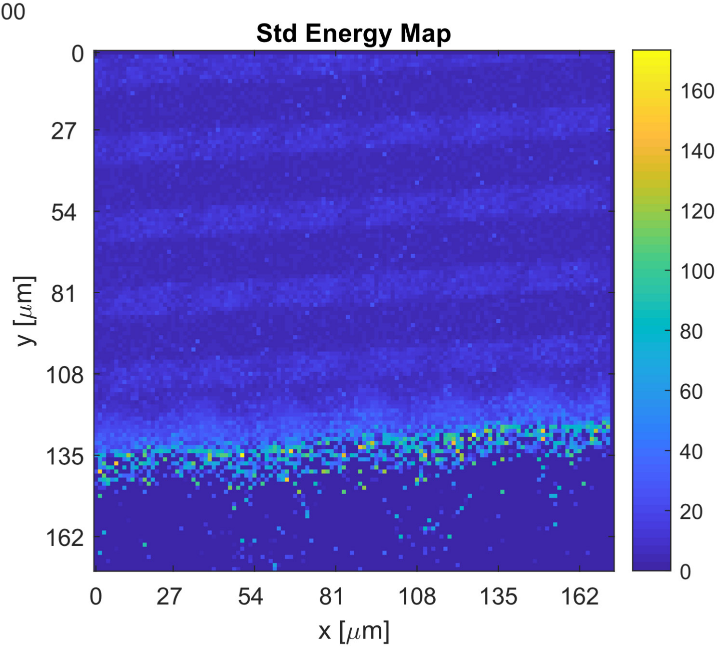


The 10 bit ADC (1024 channels) scale goes from 0 to 10 V (e.g. $\text{Ch.}600 \cong 6V$) and it's connected to the selected pixel's output through a readout chain comprised of a bias-T preamplifier and a pulse shaper.

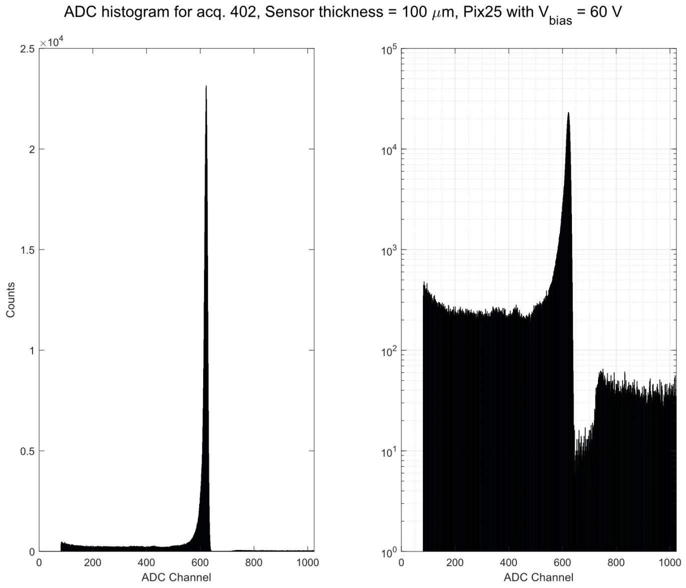
1. The ADC histogram is generated from the ADC counts for each (x, y) couple. A cut on noise and pile-ups can be performed (e.g. [450, 700])
2. The maps with the validated energies is output with the standard deviation of each averaged energy

SCAN STUDY





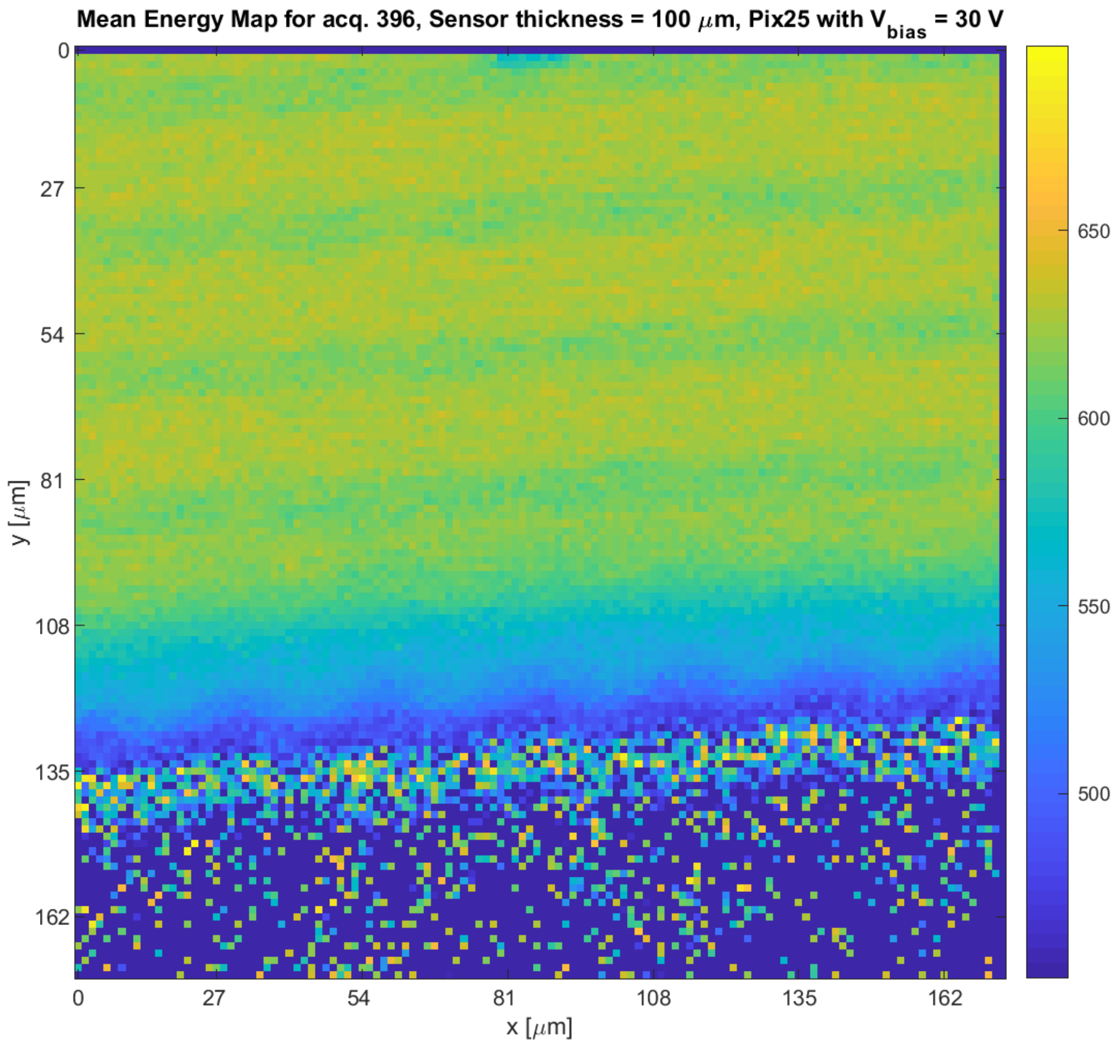
1. The ADC histogram is generated from the ADC counts for each (x, y) couple. A cut on noise and pile-ups can be performed (e.g. [450, 700])
2. The maps with the validated energies is output with the standard deviation of each averaged energy



100 µm

100 µm THICK SENSOR MAP RESULT

30 V

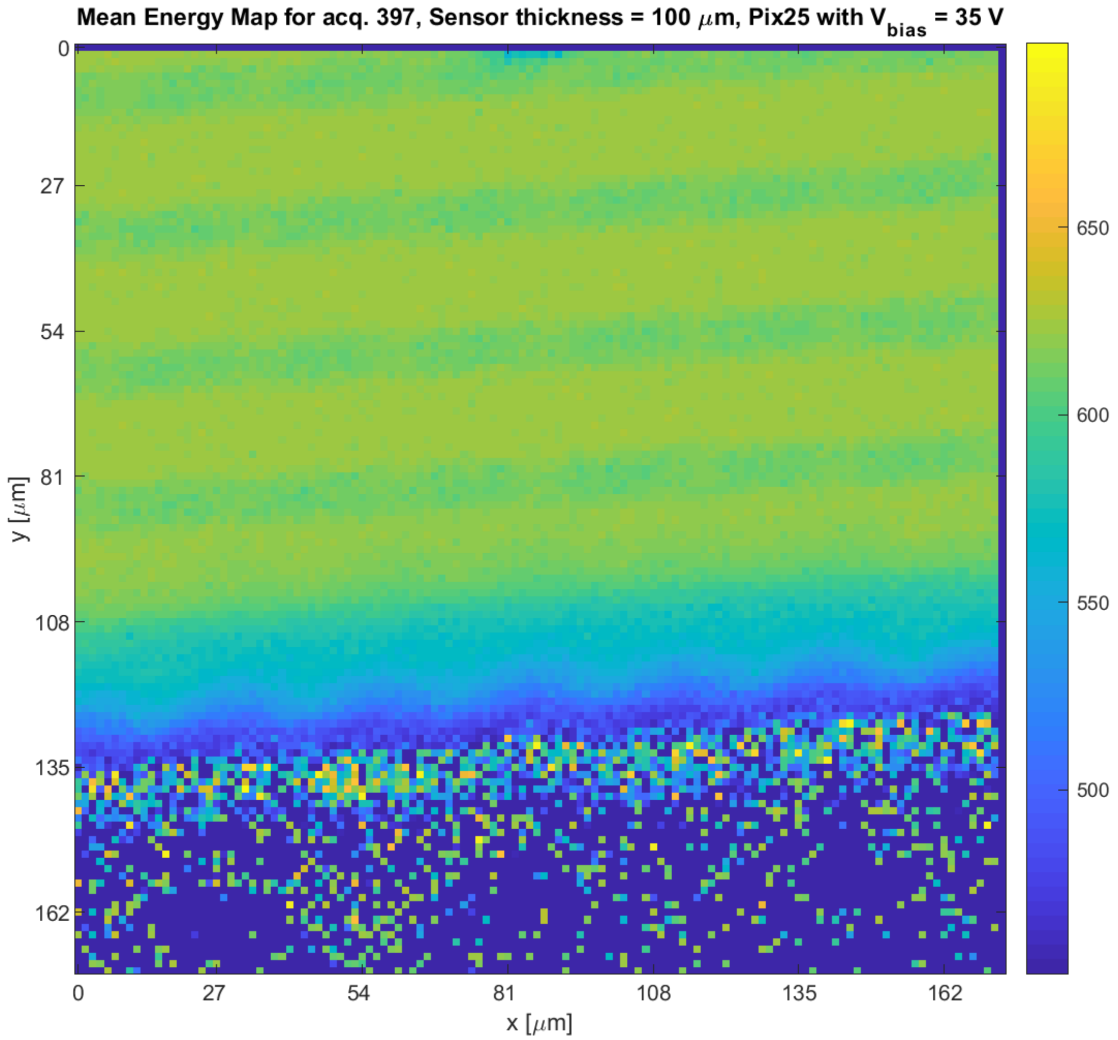


Considering the 25 µm pixel pitch on the 100 µm thick sensor, by increasing the bias voltage these characteristics can be noticed:

- An improvement on the edge’s electric field
- An increased charge collection uniformity

100 µm THICK SENSOR MAP RESULT

35 V

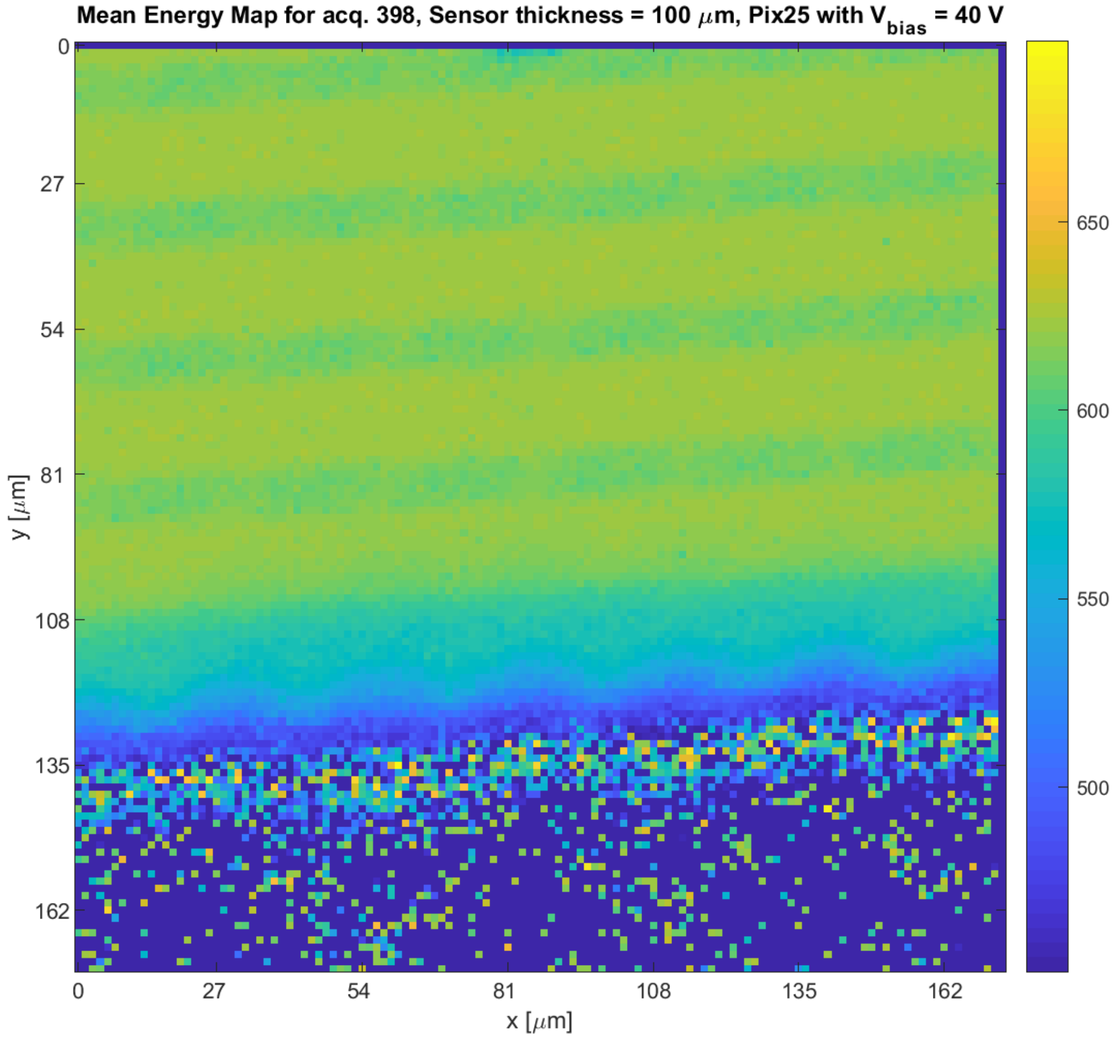


Considering the 25 µm pixel pitch on the 100 µm thick sensor, by increasing the bias voltage these characteristics can be noticed:

- An improvement on the edge's electric field
- An increased charge collection uniformity

100 µm THICK SENSOR MAP RESULT

40 V

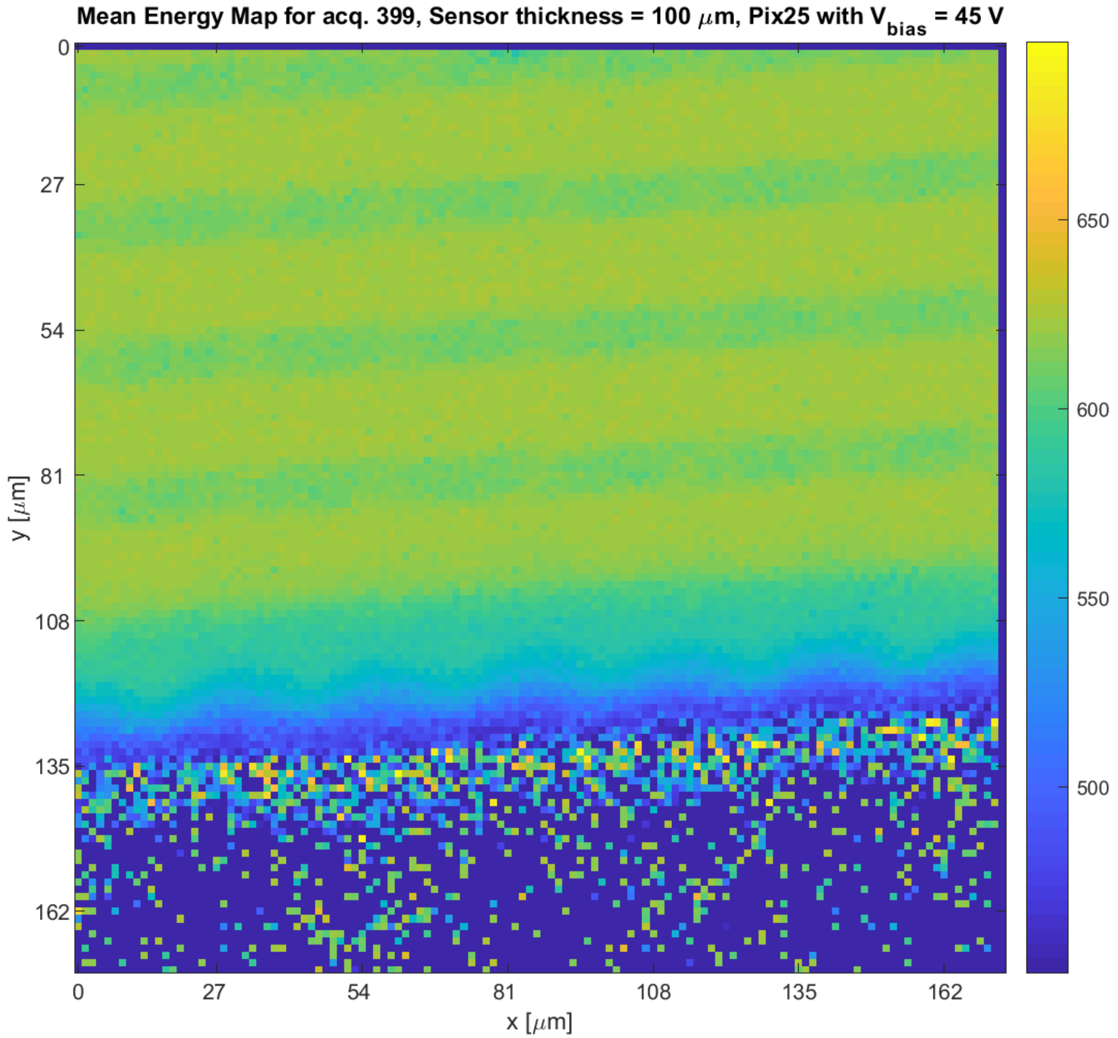


Considering the 25 µm pixel pitch on the 100 µm thick sensor, by increasing the bias voltage these characteristics can be noticed:

- An improvement on the edge's electric field
- An increased charge collection uniformity

100 µm THICK SENSOR MAP RESULT

45 V

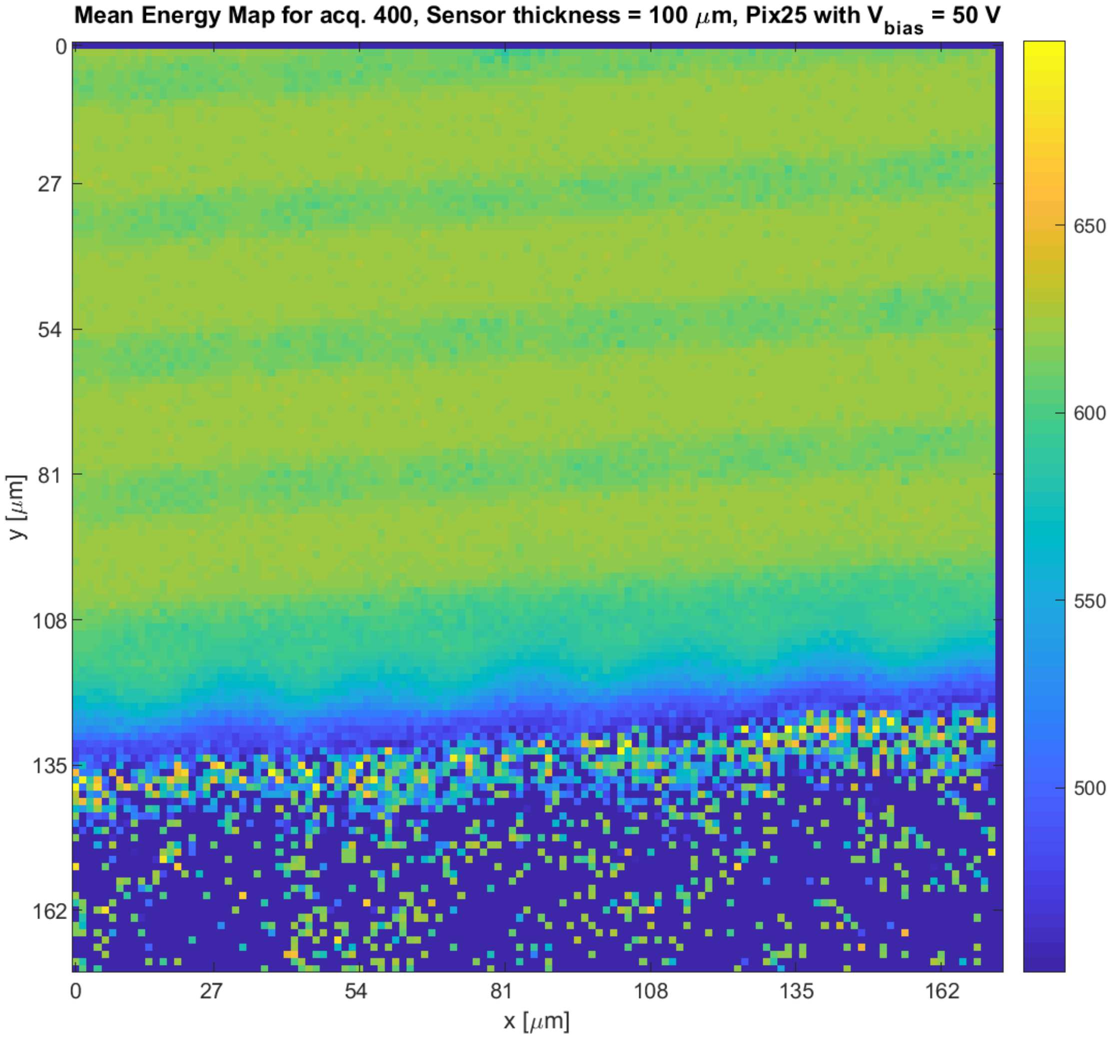


Considering the 25 µm pixel pitch on the 100 µm thick sensor, by increasing the bias voltage these characteristics can be noticed:

- An improvement on the edge’s electric field
- An increased charge collection uniformity

100 µm THICK SENSOR MAP RESULT

50 V

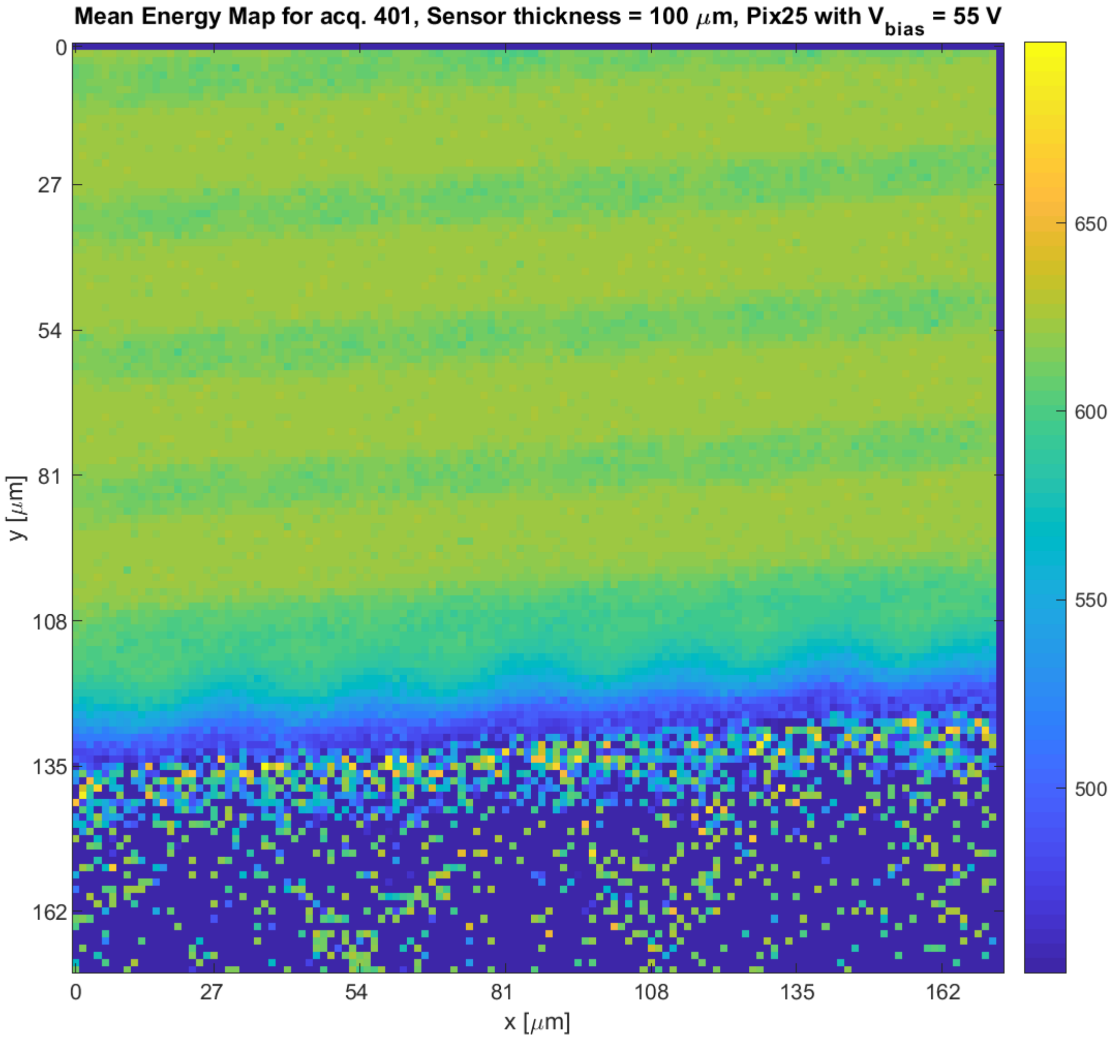


Considering the 25 µm pixel pitch on the 100 µm thick sensor, by increasing the bias voltage these characteristics can be noticed:

- An improvement on the edge’s electric field
- An increased charge collection uniformity

100 µm THICK SENSOR MAP RESULT

55 V

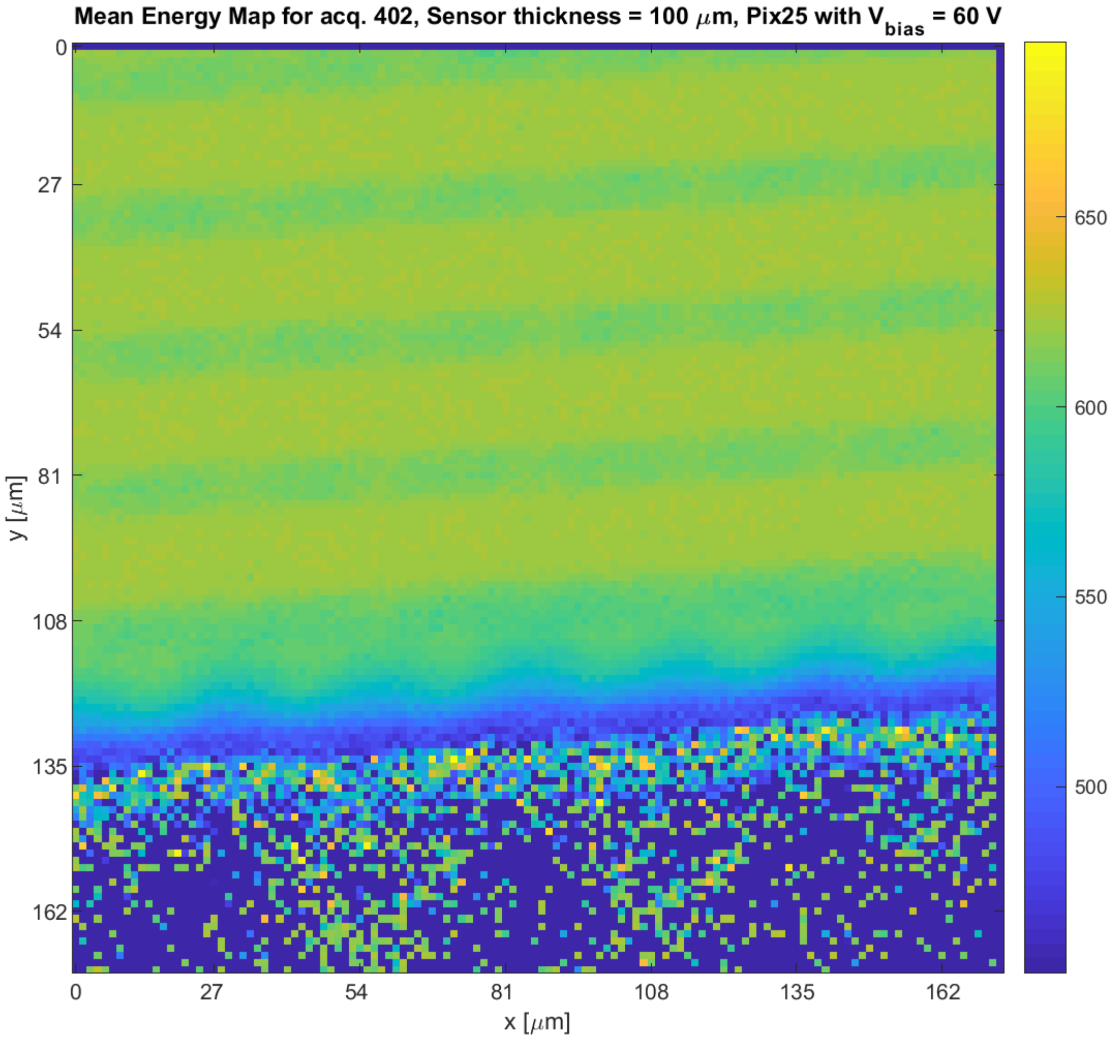


Considering the 25 µm pixel pitch on the 100 µm thick sensor, by increasing the bias voltage these characteristics can be noticed:

- An improvement on the edge's electric field
- An increased charge collection uniformity

100 µm THICK SENSOR MAP RESULT

60 V

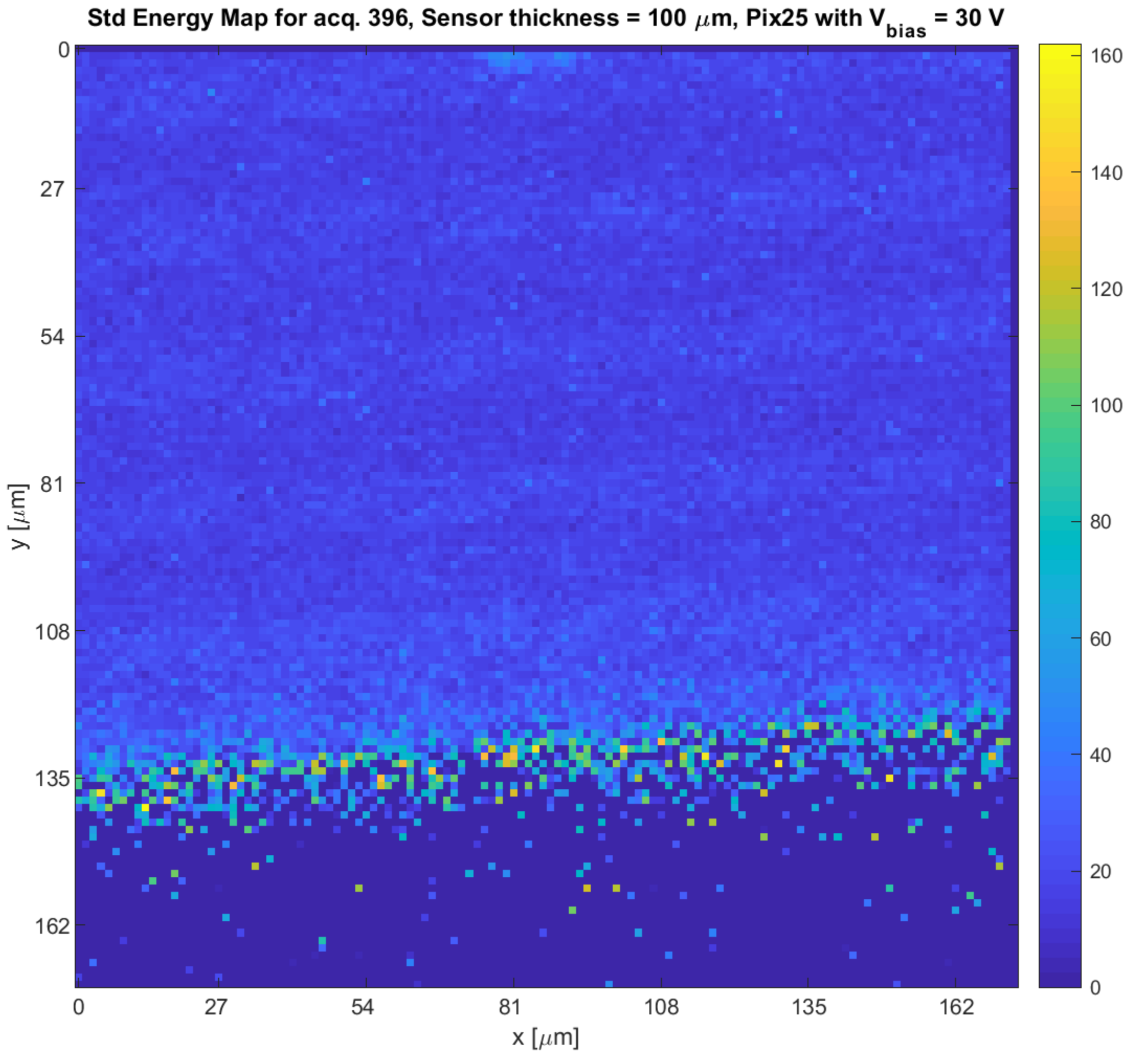


Considering the 25 µm pixel pitch on the 100 µm thick sensor, by increasing the bias voltage these characteristics can be noticed:

- An improvement on the edge's electric field
- An increased charge collection uniformity

100 µm THICK SENSOR STD RESULT

30 V



Standard deviation of the energy measurement in each pixel hit.

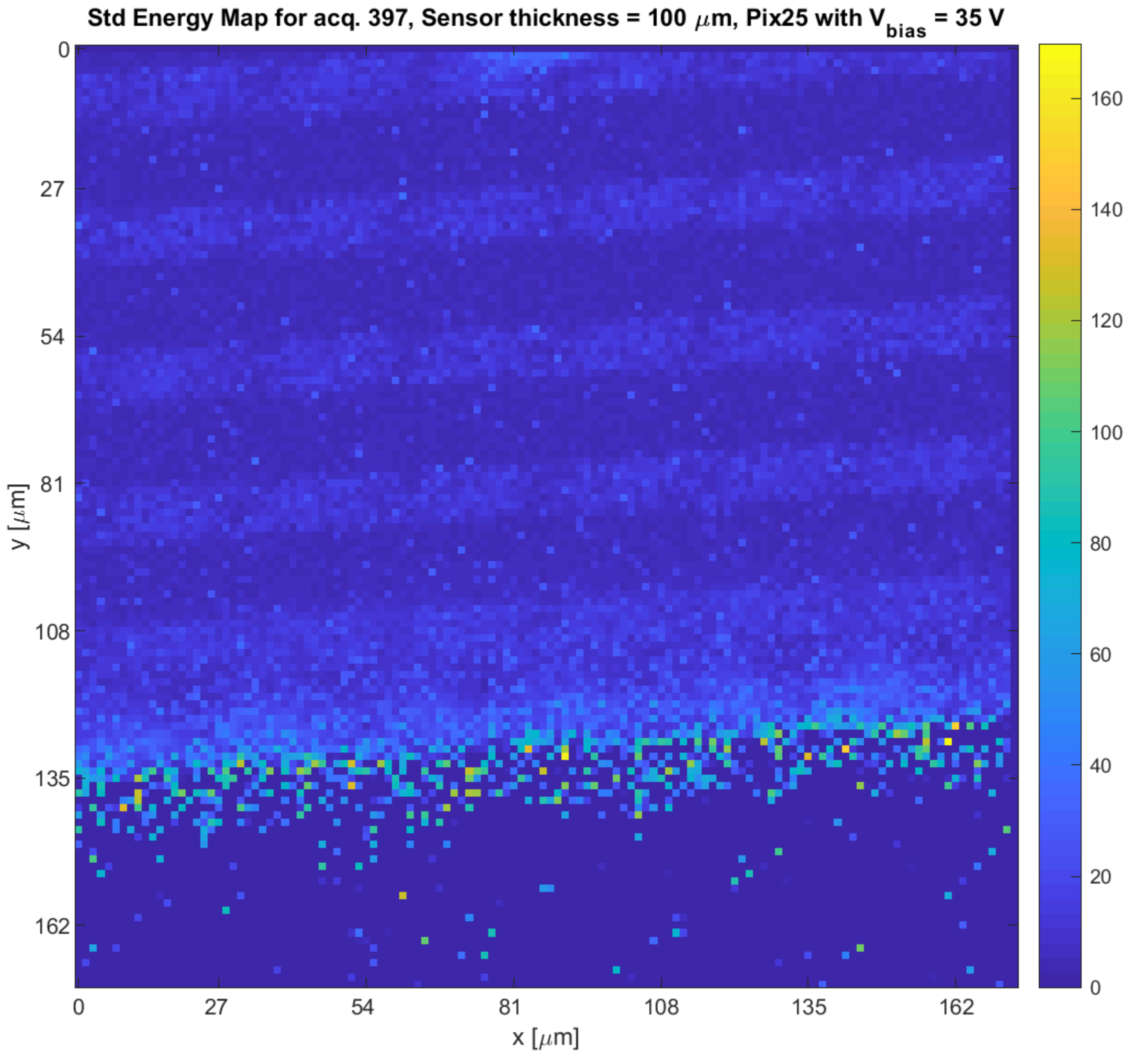
On the left, the non perfectly depleted area ($V_{HV} = 30V$) causes the output voltage baseline to fluctuate (the detector's capacitance is higher at lower voltages) giving rise to high noise, thus the structure is barely visible.

When increasing the bias voltage the std decreases and, in turn, the charge collection uniformity increases.

Furthermore, the metal lines are perfectly visible, this result is expected, considering the protons' Landau energy absorption distribution.

100 µm THICK SENSOR STD RESULT

35 V



Standard deviation of the energy measurement in each pixel hit.

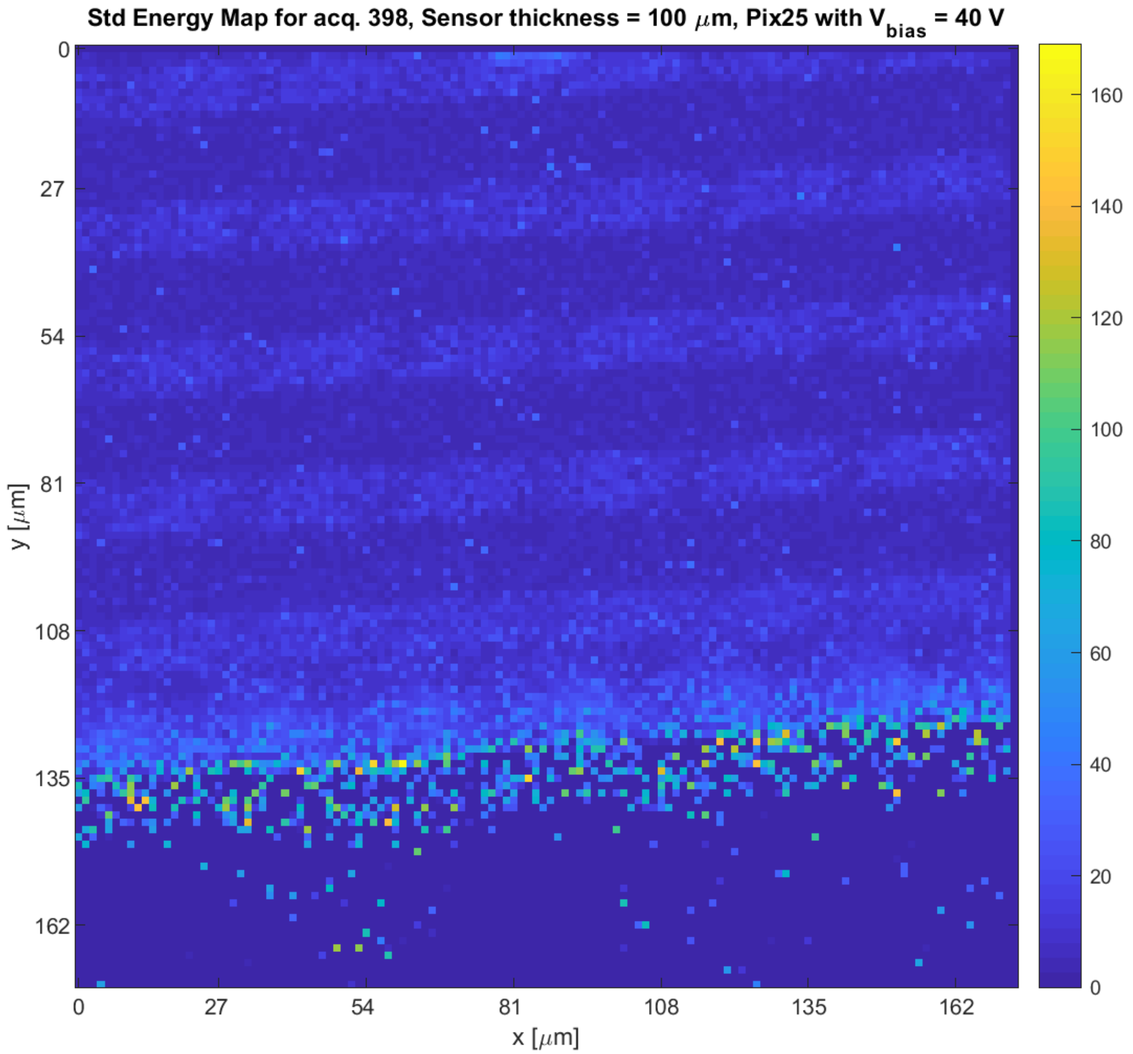
On the left, the non perfectly depleted area ($V_{HV} = 30V$) causes the output voltage baseline to fluctuate (the detector's capacitance is higher at lower voltages) giving rise to high noise, thus the structure is barely visible.

When increasing the bias voltage the std decreases and, in turn, the charge collection uniformity increases.

Furthermore, the metal lines are perfectly visible, this result is expected, considering the protons' Landau energy absorption distribution.

100 μm THICK SENSOR STD RESULT

40 V



Standard deviation of the energy measurement in each pixel hit.

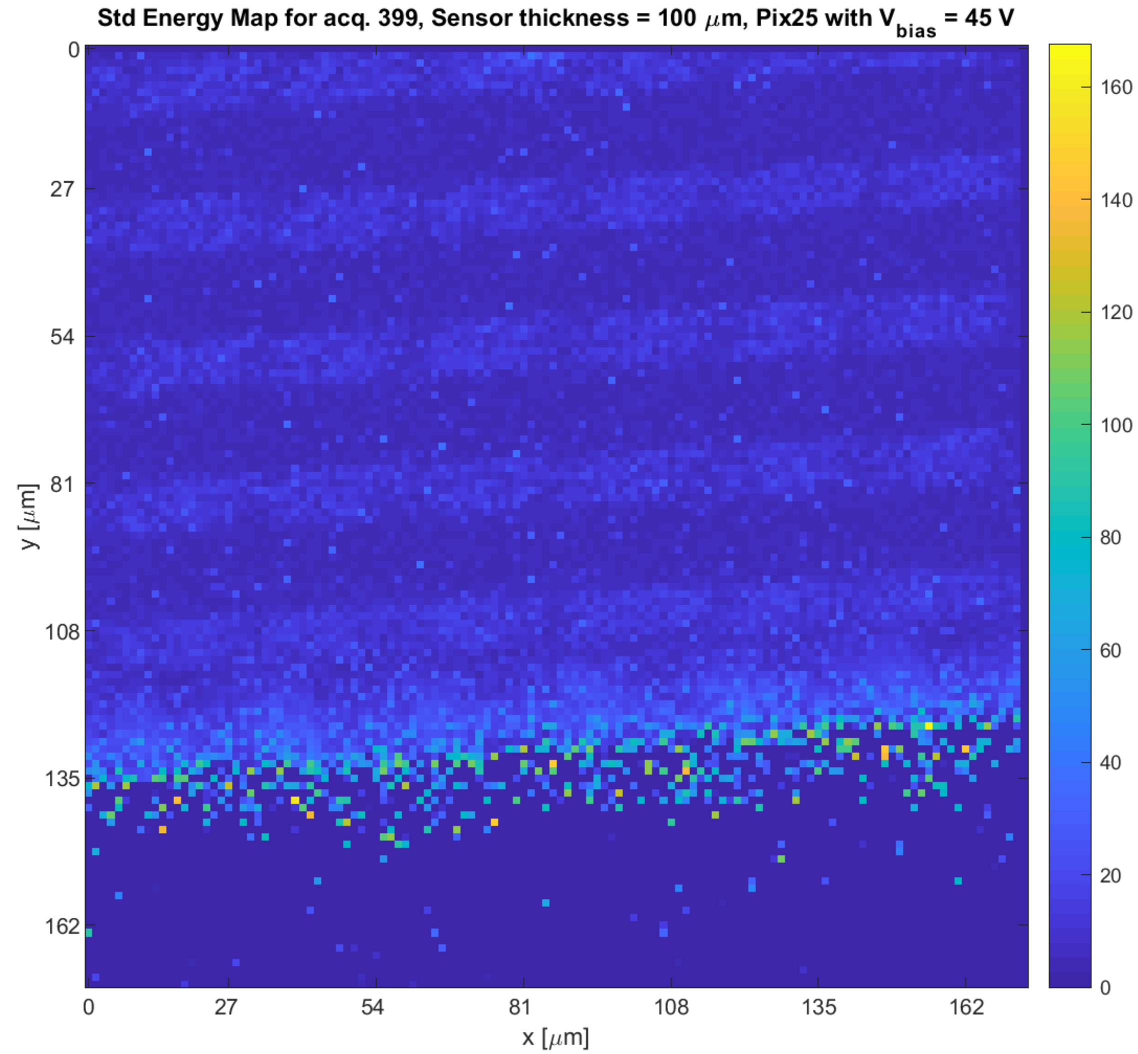
On the left, the non perfectly depleted area ($V_{HV} = 30V$) causes the output voltage baseline to fluctuate (the detector's capacitance is higher at lower voltages) giving rise to high noise, thus the structure is barely visible.

When increasing the bias voltage the std decreases and, in turn, the charge collection uniformity increases.

Furthermore, the metal lines are perfectly visible, this result is expected, considering the protons' Landau energy absorption distribution.

100 µm THICK SENSOR STD RESULT

45 V



Standard deviation of the energy measurement in each pixel hit.

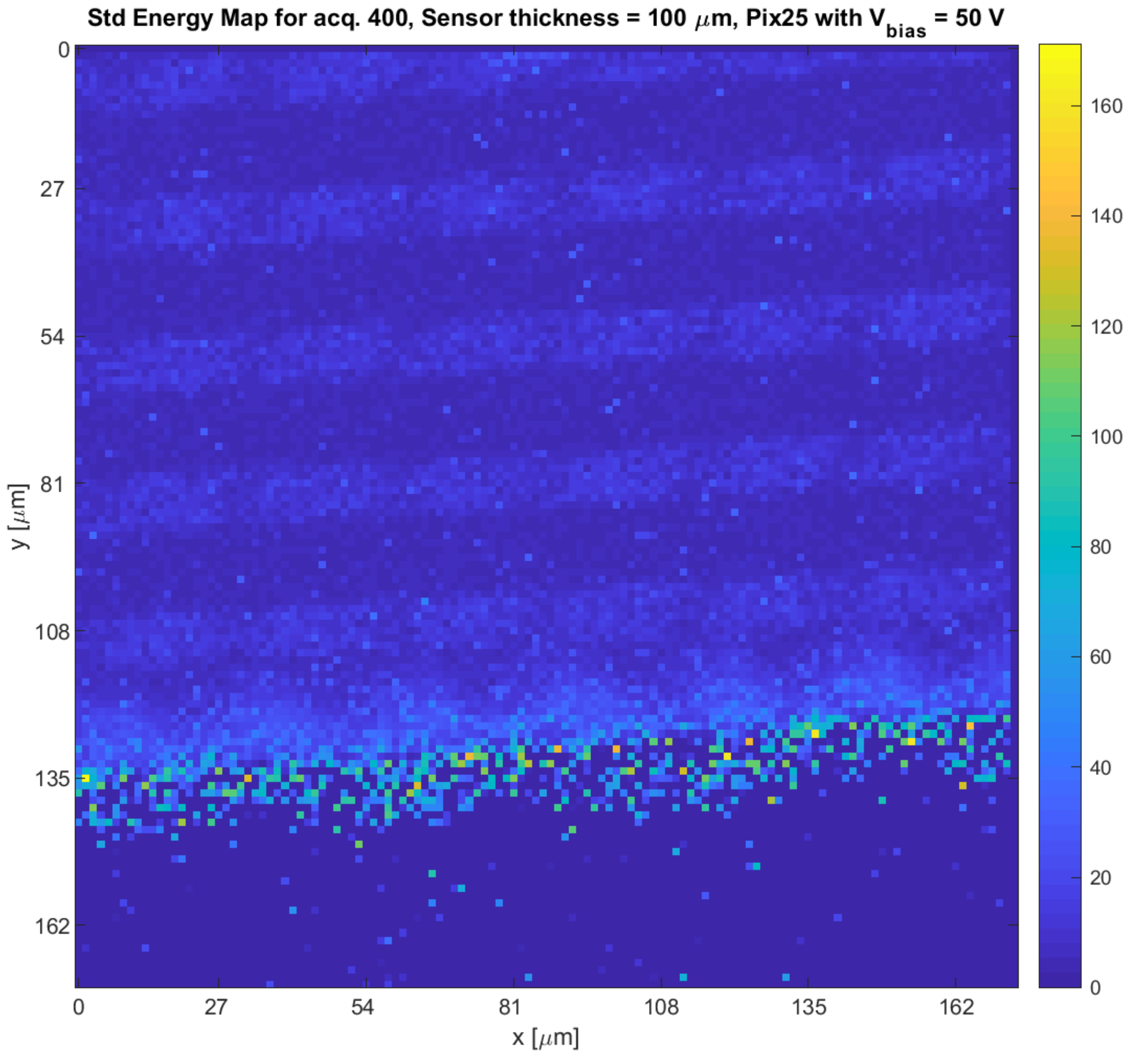
On the left, the non perfectly depleted area ($V_{HV} = 30V$) causes the output voltage baseline to fluctuate (the detector's capacitance is higher at lower voltages) giving rise to high noise, thus the structure is barely visible.

When increasing the bias voltage the std decreases and, in turn, the charge collection uniformity increases.

Furthermore, the metal lines are perfectly visible, this result is expected, considering the protons' Landau energy absorption distribution.

100 µm THICK SENSOR STD RESULT

50 V



Standard deviation of the energy measurement in each pixel hit.

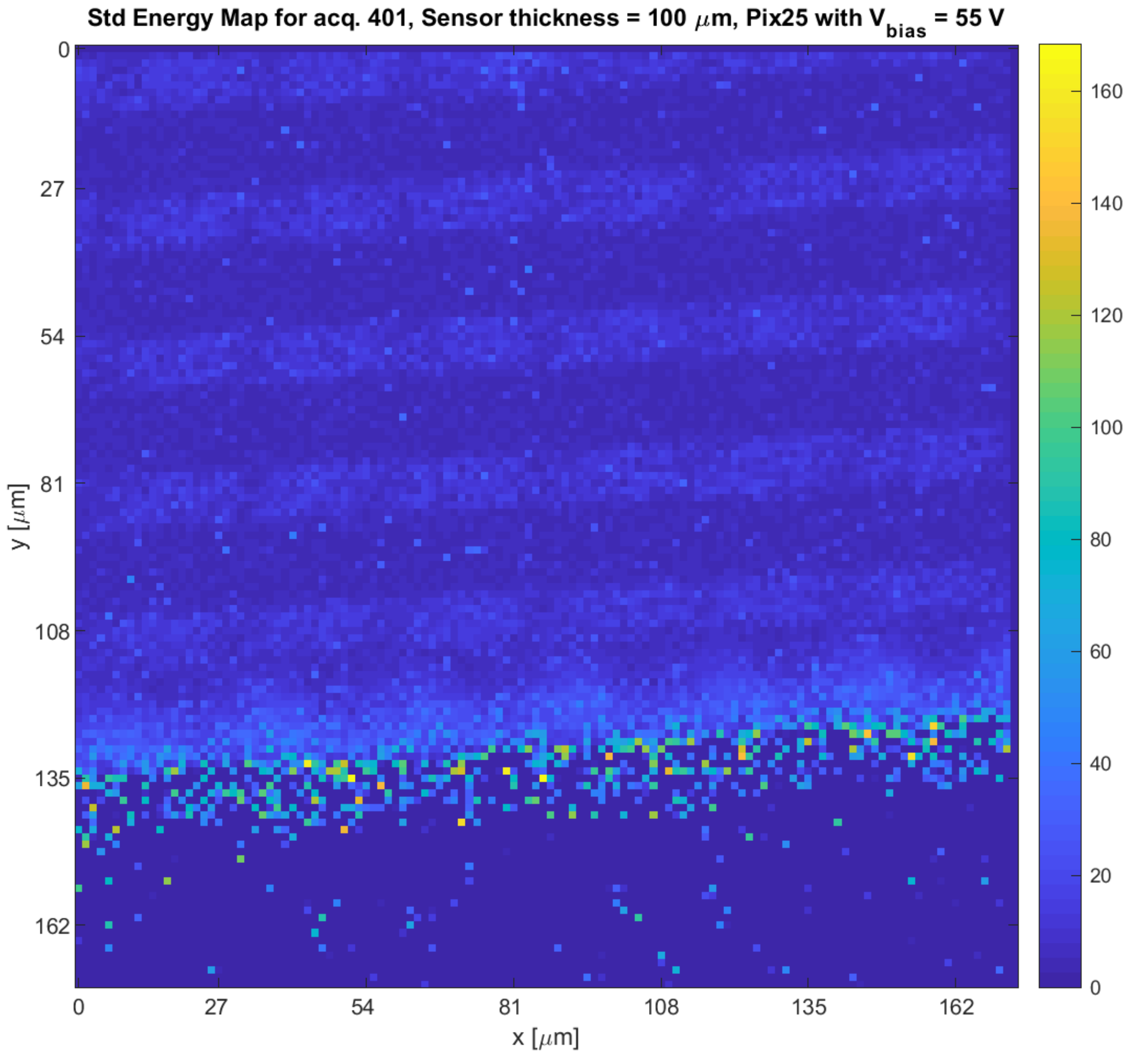
On the left, the non perfectly depleted area ($V_{HV} = 30V$) causes the output voltage baseline to fluctuate (the detector's capacitance is higher at lower voltages) giving rise to high noise, thus the structure is barely visible.

When increasing the bias voltage the std decreases and, in turn, the charge collection uniformity increases.

Furthermore, the metal lines are perfectly visible, this result is expected, considering the protons' Landau energy absorption distribution.

100 µm THICK SENSOR STD RESULT

55 V



Standard deviation of the energy measurement in each pixel hit.

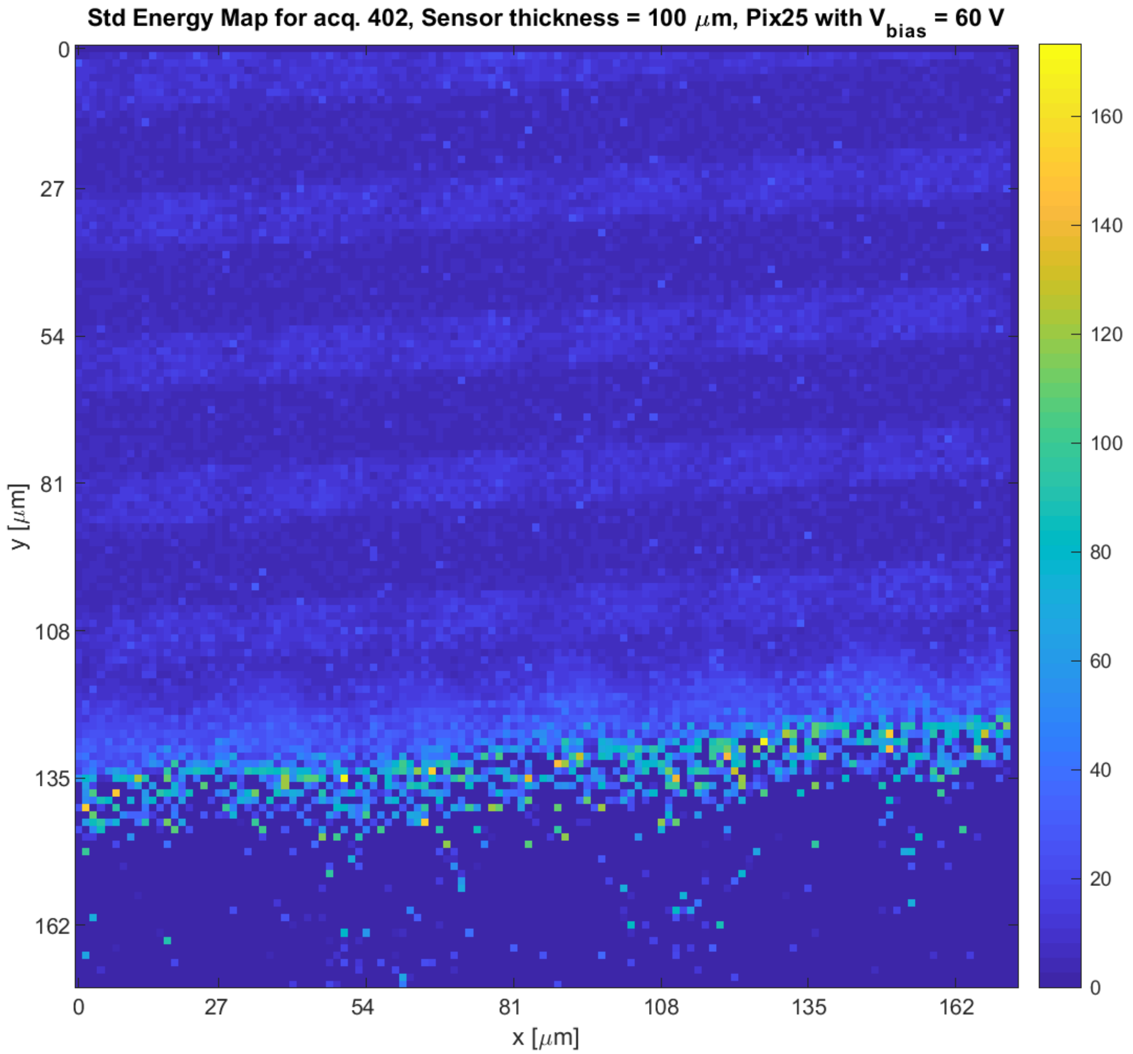
On the left, the non perfectly depleted area ($V_{HV} = 30V$) causes the output voltage baseline to fluctuate (the detector's capacitance is higher at lower voltages) giving rise to high noise, thus the structure is barely visible.

When increasing the bias voltage the std decreases and, in turn, the charge collection uniformity increases.

Furthermore, the metal lines are perfectly visible, this result is expected, considering the protons' Landau energy absorption distribution.

100 µm THICK SENSOR STD RESULT

60 V



Standard deviation of the energy measurement in each pixel hit.

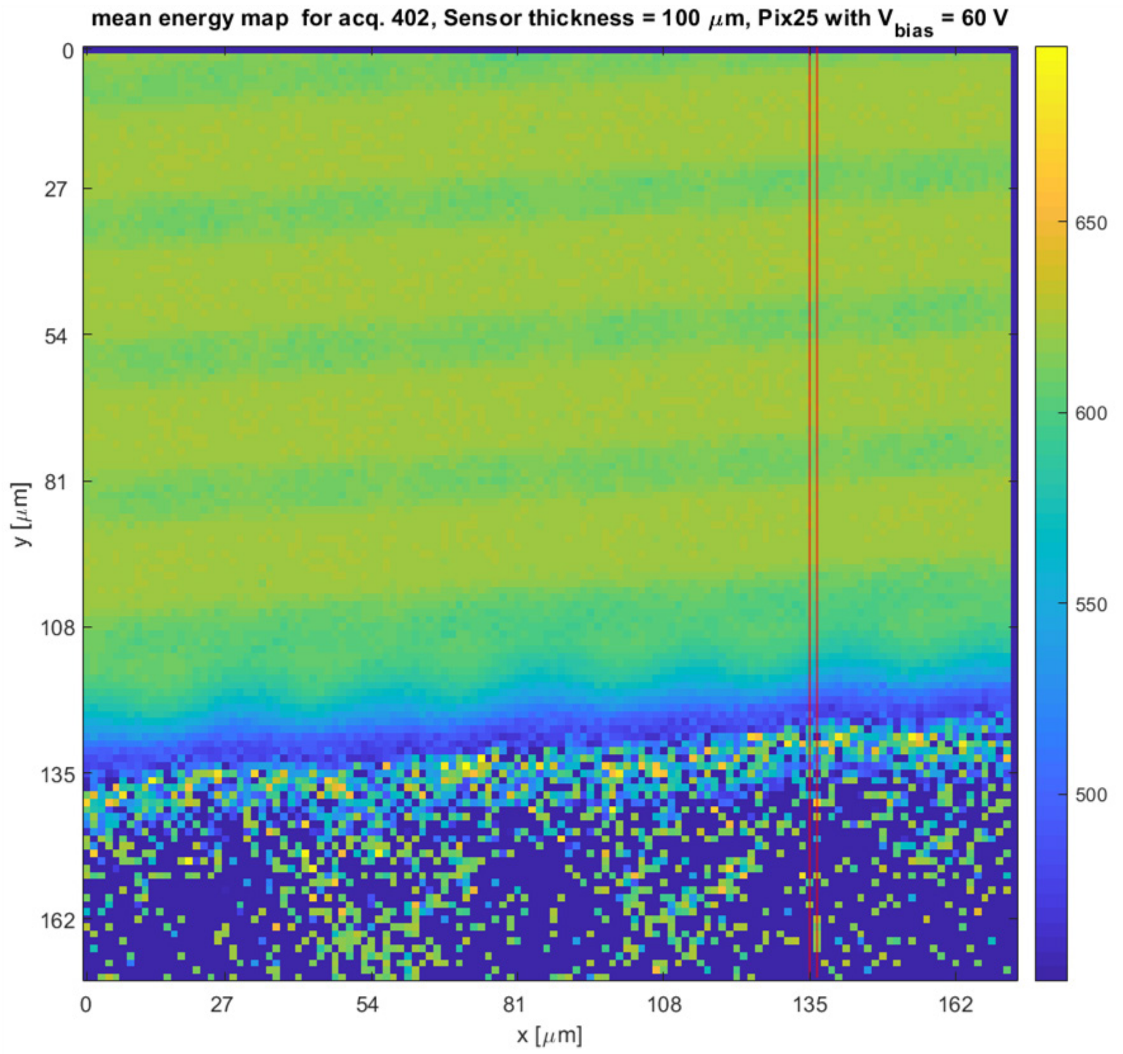
On the left, the non perfectly depleted area ($V_{HV} = 30V$) causes the output voltage baseline to fluctuate (the detector's capacitance is higher at lower voltages) giving rise to high noise, thus the structure is barely visible.

When increasing the bias voltage the std decreases and, in turn, the charge collection uniformity increases.

Furthermore, the metal lines are perfectly visible, this result is expected, considering the protons' Landau energy absorption distribution.

100 µm THICK SENSOR MAP CUT RESULT

60 V



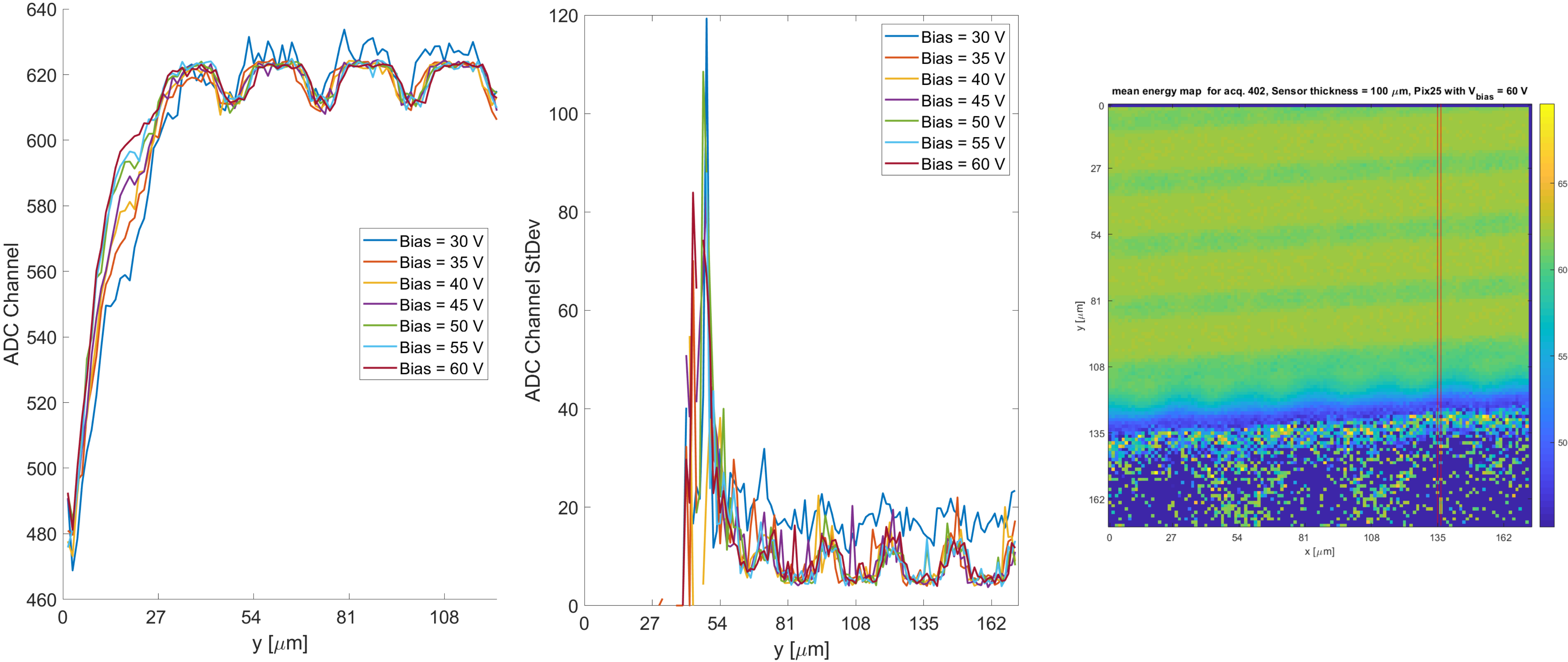
Increasing the bias voltage the noticed characteristics:

- An improvement on the edge's electric field
- An increased charge collection uniformity

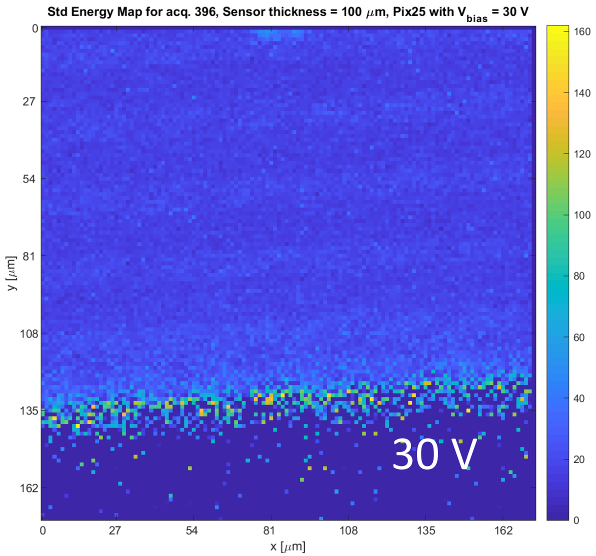
These results can be corroborated by a vertical cut along the y-axis on the map.

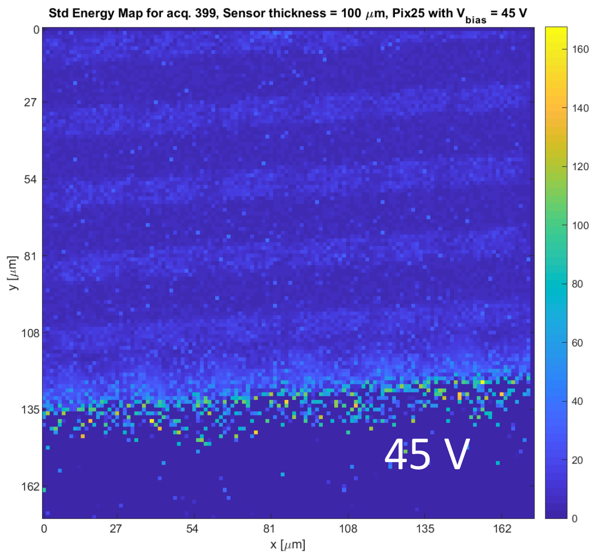
100 µm SENSOR CUT RESULT

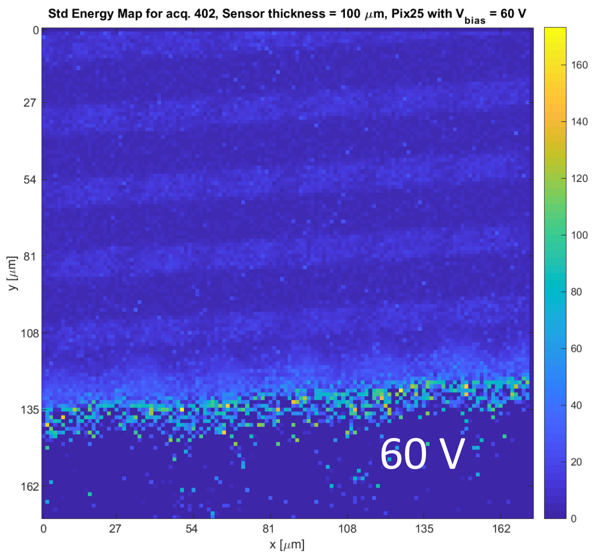
Vertical cut on the energy and standard deviation map with varying bias voltages:



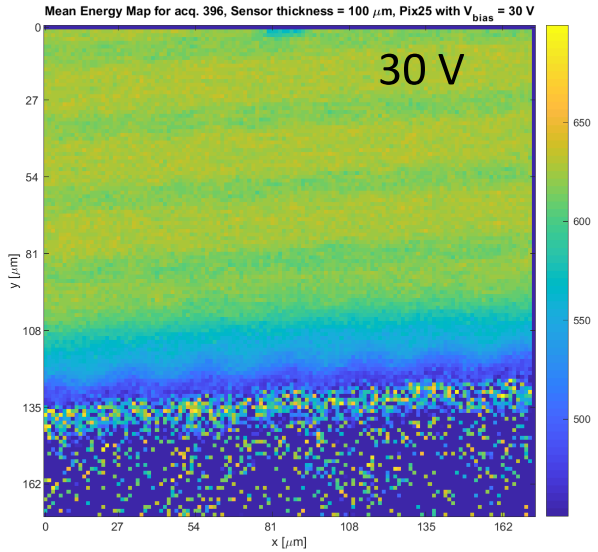
100 µm RESULT OVERVIEW

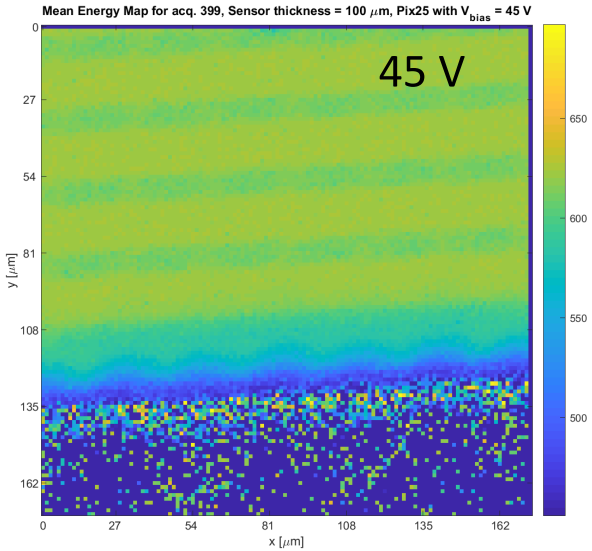

Std Energy Map for acq. 396, Sensor thickness = 100 μm, Pix25 with V_{bias} = 30 V

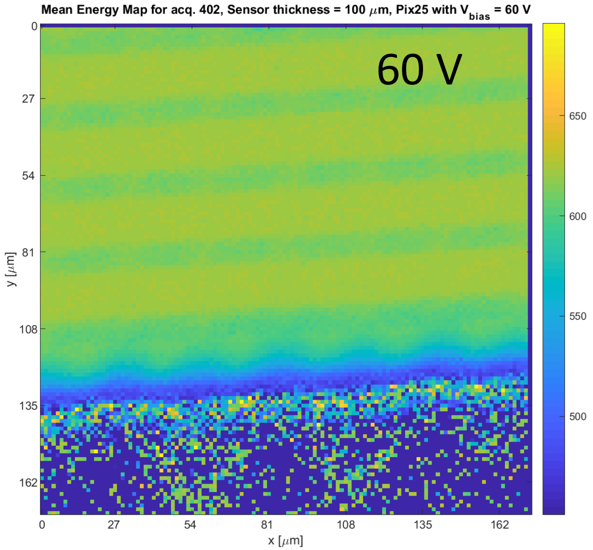

Std Energy Map for acq. 399, Sensor thickness = 100 μm, Pix25 with V_{bias} = 45 V


Std Energy Map for acq. 402, Sensor thickness = 100 μm, Pix25 with V_{bias} = 60 V

Bias Voltage


Mean Energy Map for acq. 396, Sensor thickness = 100 μm, Pix25 with V_{bias} = 30 V


Mean Energy Map for acq. 399, Sensor thickness = 100 μm, Pix25 with V_{bias} = 45 V


Mean Energy Map for acq. 402, Sensor thickness = 100 μm, Pix25 with V_{bias} = 60 V

Standard deviation of the energy versus the energy map.

Perfect collection efficiency within the sensor

The 100 µm sensor, when working below the full depletion voltage suffers from very high noise which disappears once the full depletion voltage is reached.

This phenomena can be explained by the higher input capacitance at lower depletion voltages.

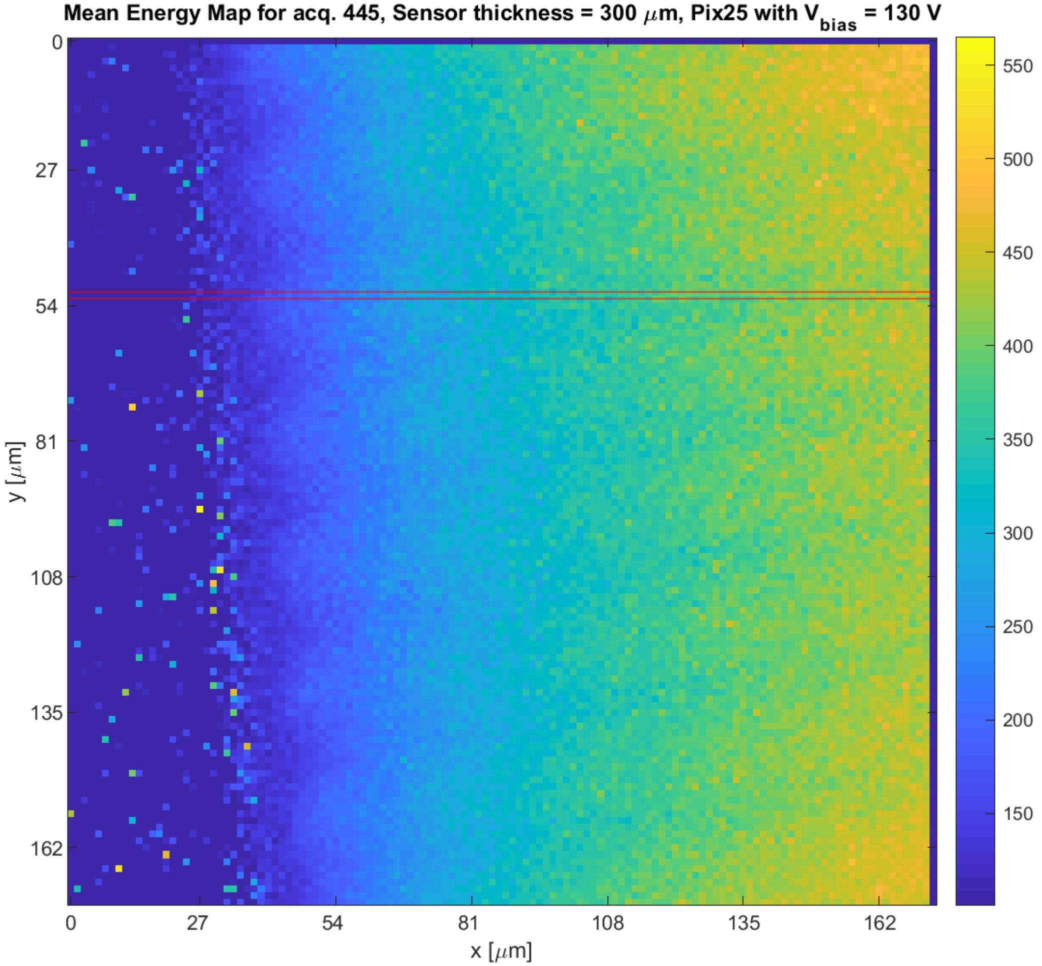
The full depletion voltage is slightly higher than expected.

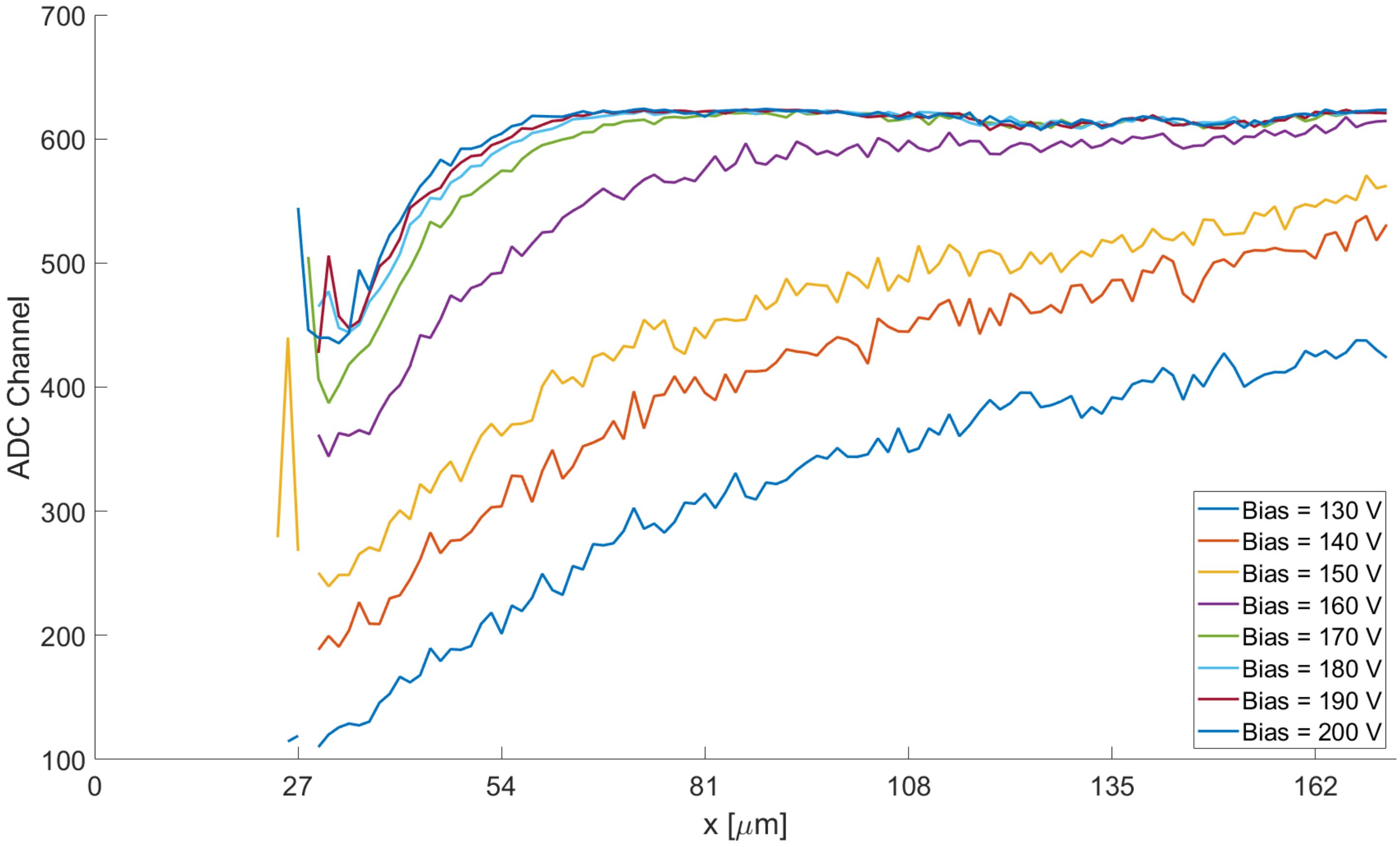
300 µm

300 µm THICK SENSOR MAP RESULT

130 V

Considering the 25 µm pixel pitch on the 300 µm PM, increasing the bias voltage the same characteristics can be noticed.



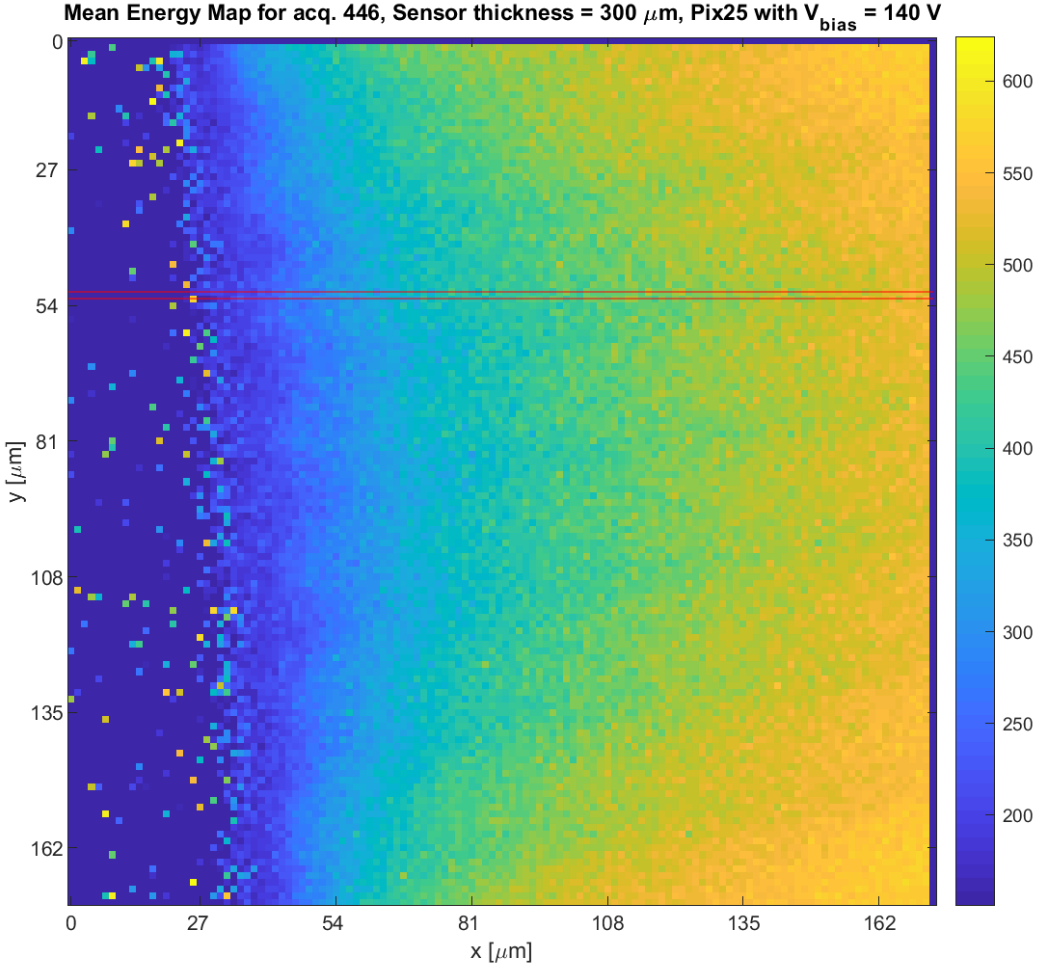


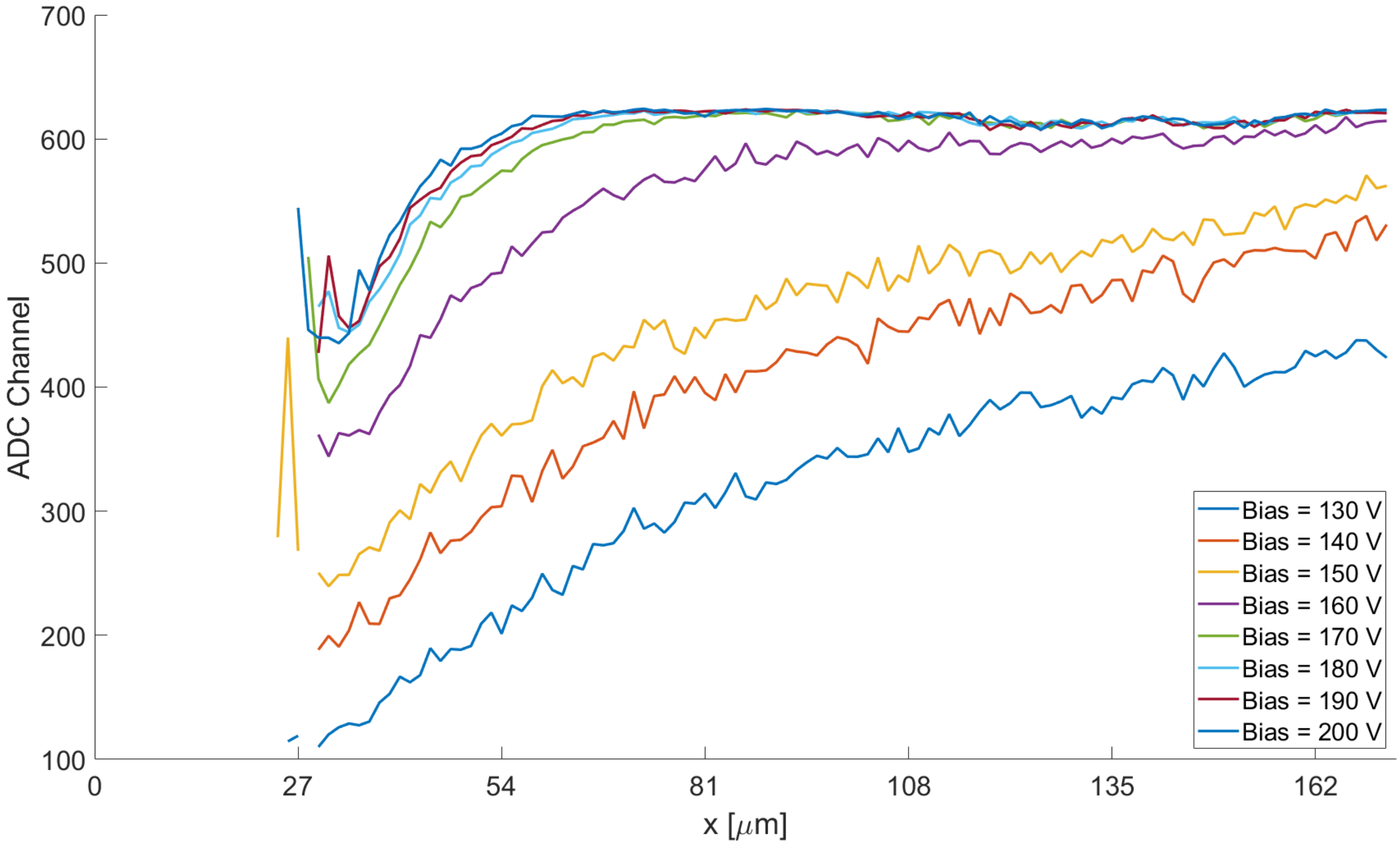
Bias Voltage variation from 130 V to 200 V

300 µm THICK SENSOR MAP RESULT

140 V

Considering the 25 µm pixel pitch on the 300 µm PM, increasing the bias voltage the same characteristics can be noticed.



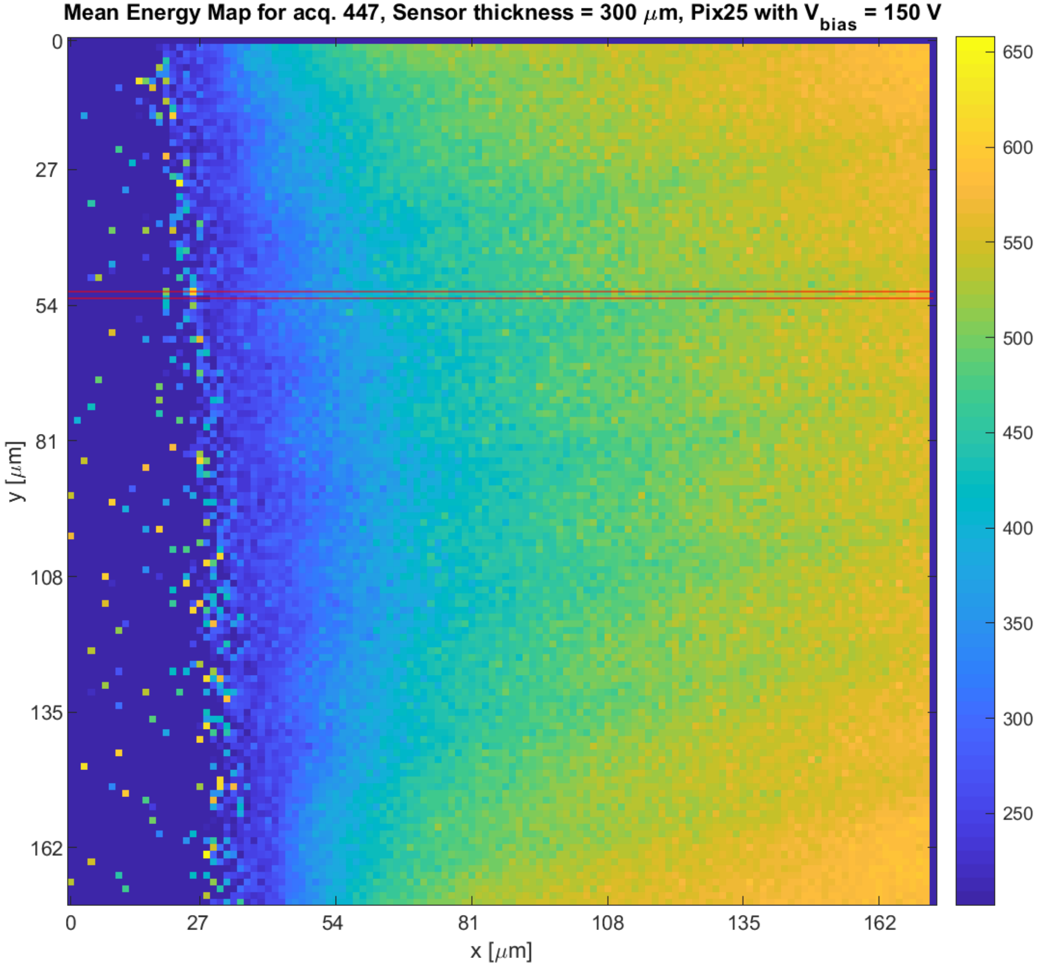


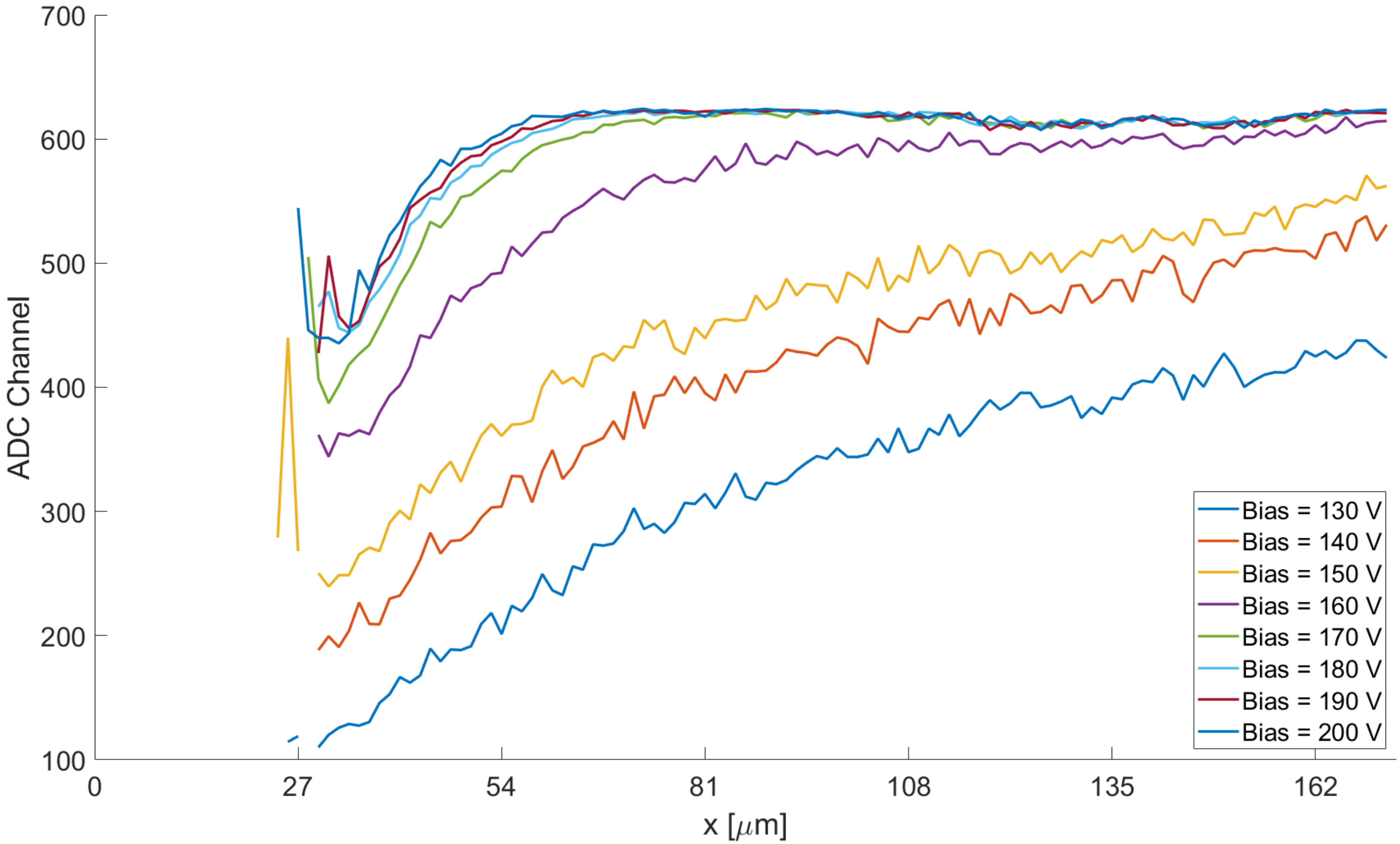
Bias Voltage variation from 130 V to 200 V

300 µm THICK SENSOR MAP RESULT

150 V

Considering the 25 µm pixel pitch on the 300 µm PM, increasing the bias voltage the same characteristics can be noticed.



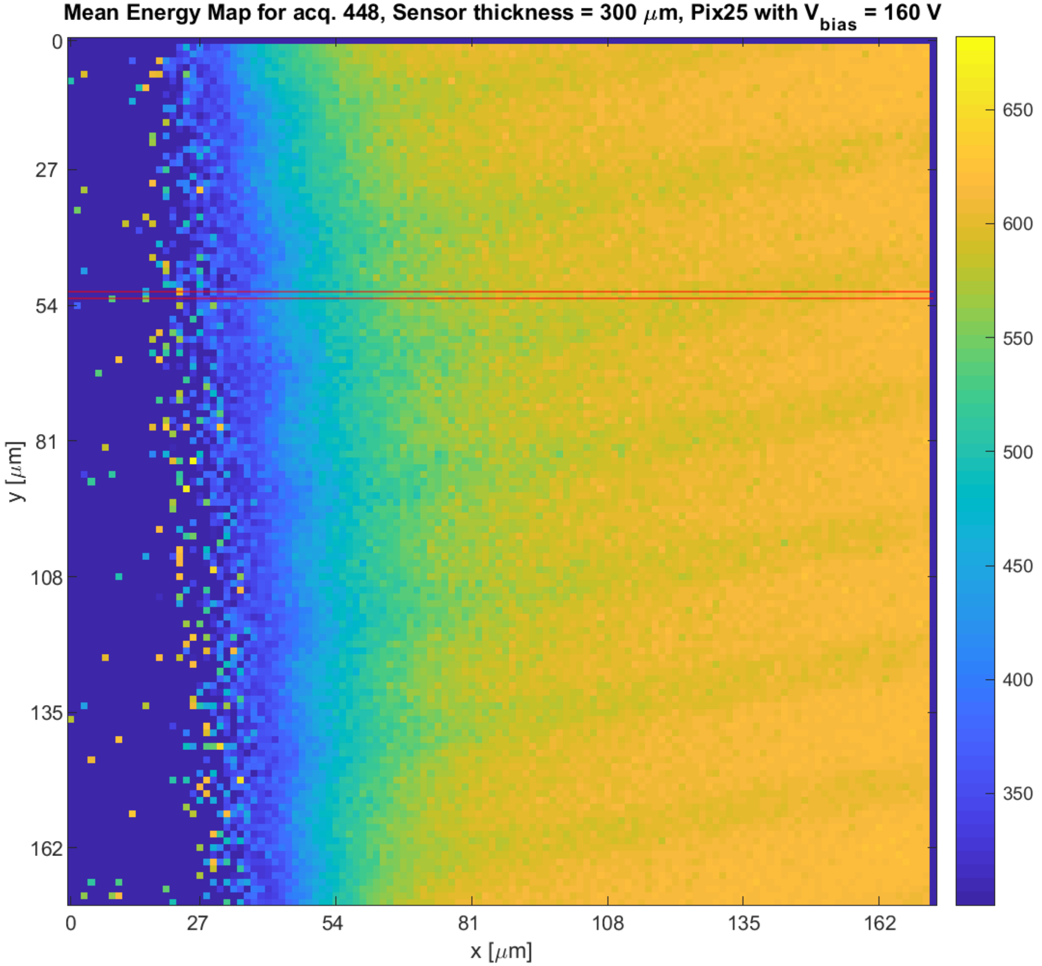


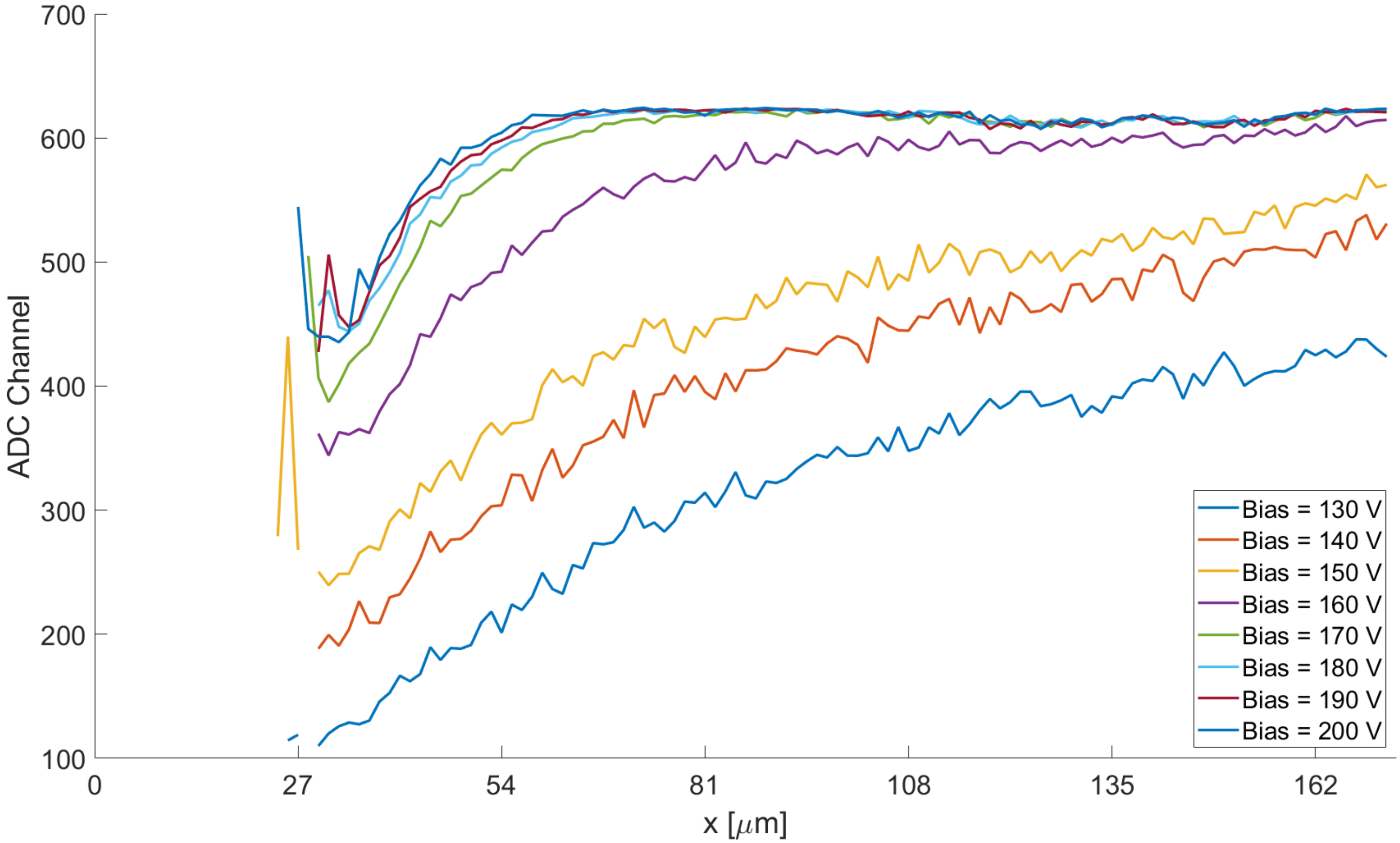
Bias Voltage variation from 130 V to 200 V

300 µm THICK SENSOR MAP RESULT

160 V

Considering the 25 µm pixel pitch on the 300 µm PM, increasing the bias voltage the same characteristics can be noticed.



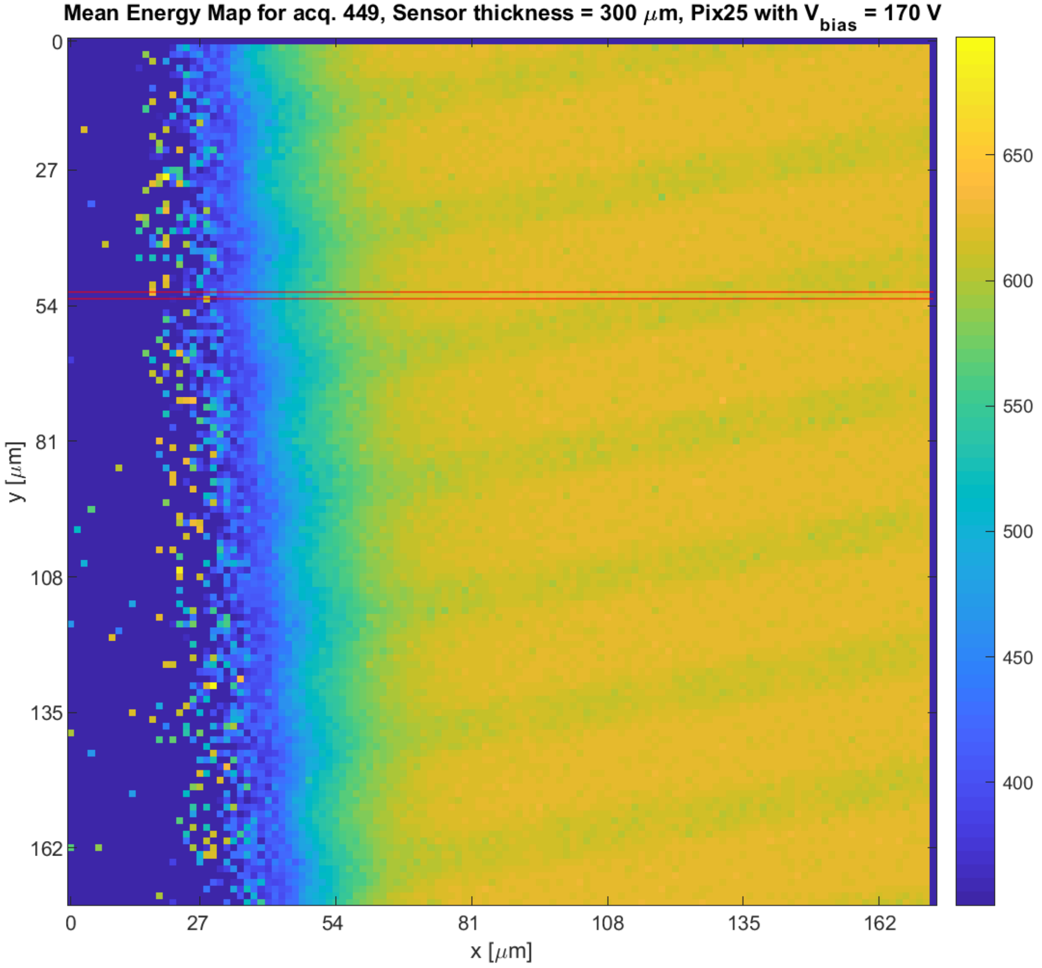


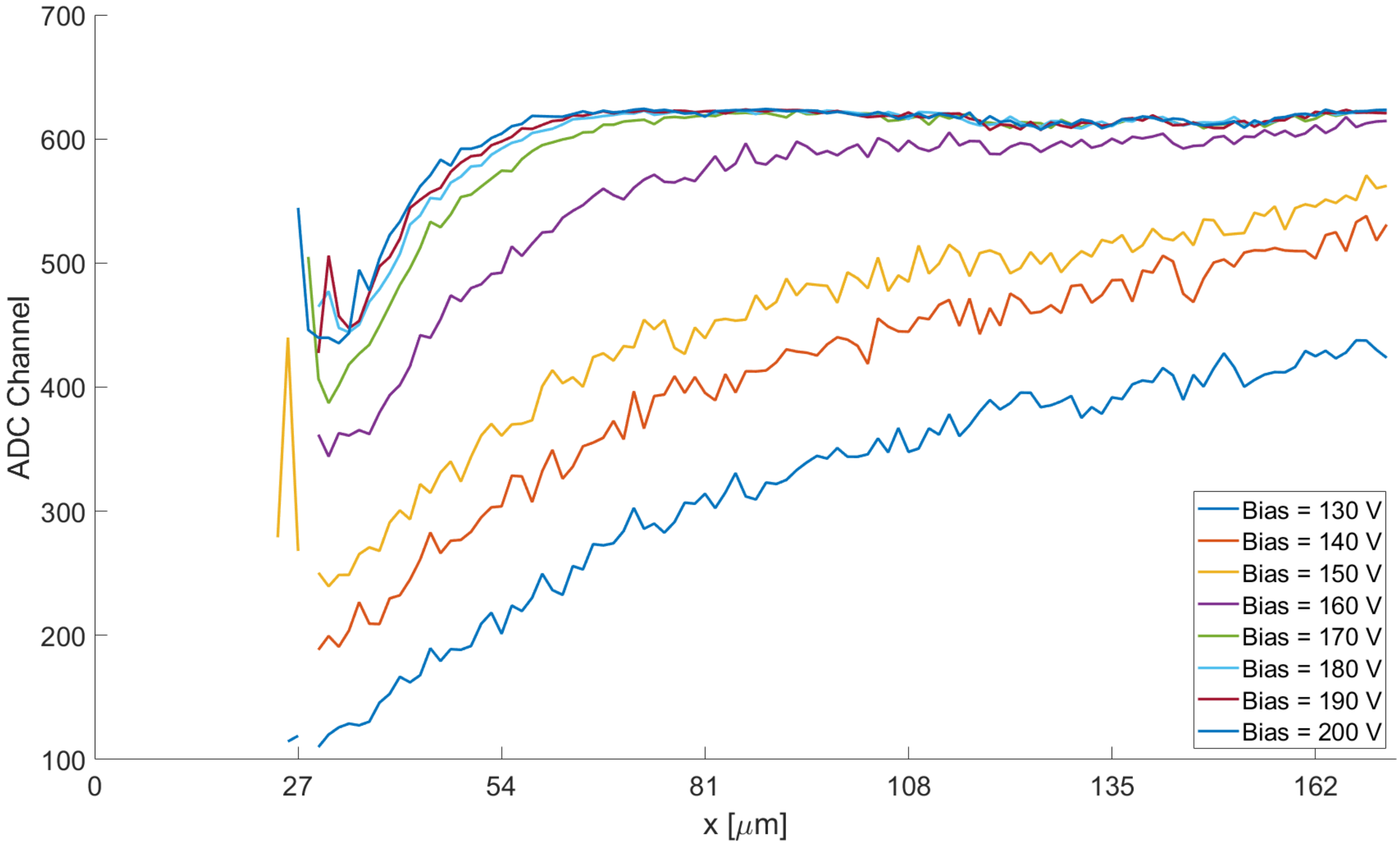
Bias Voltage variation from 130 V to 200 V

300 µm THICK SENSOR MAP RESULT

170 V

Considering the 25 µm pixel pitch on the 300 µm PM, increasing the bias voltage the same characteristics can be noticed.



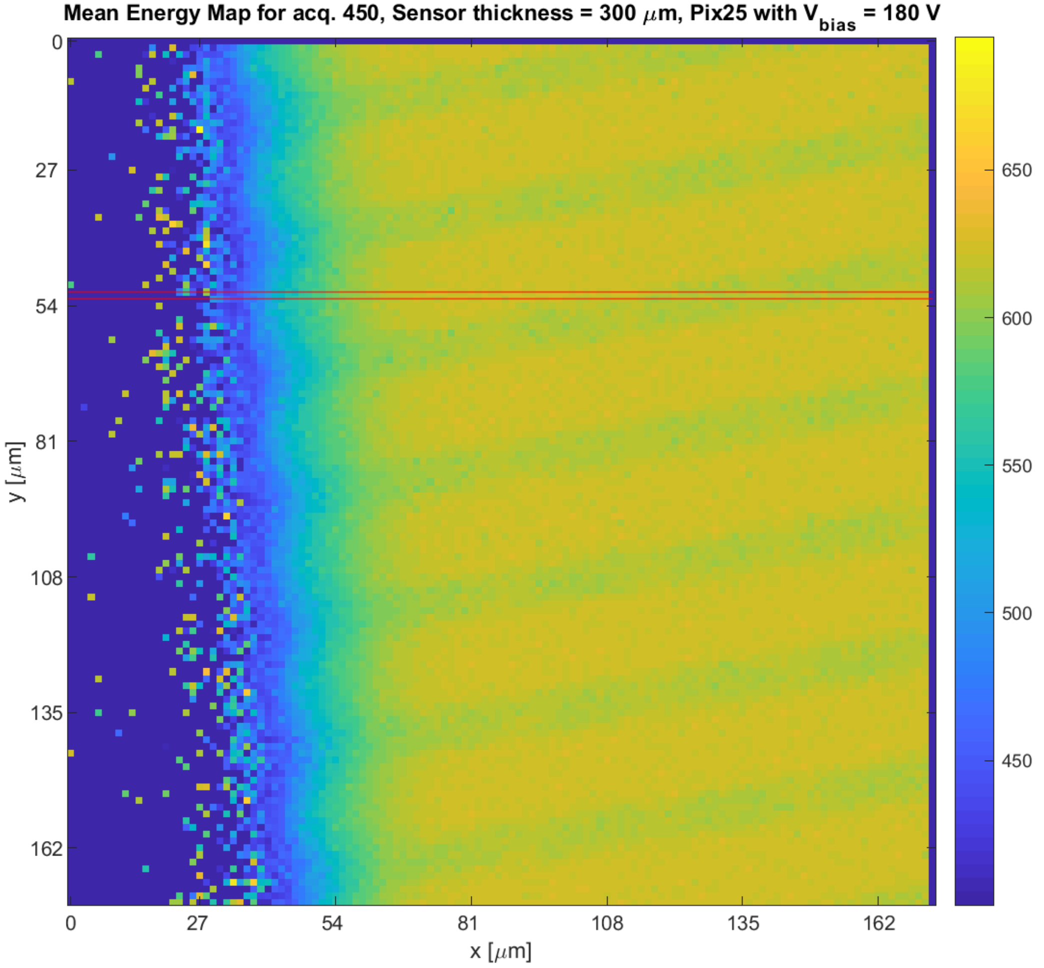


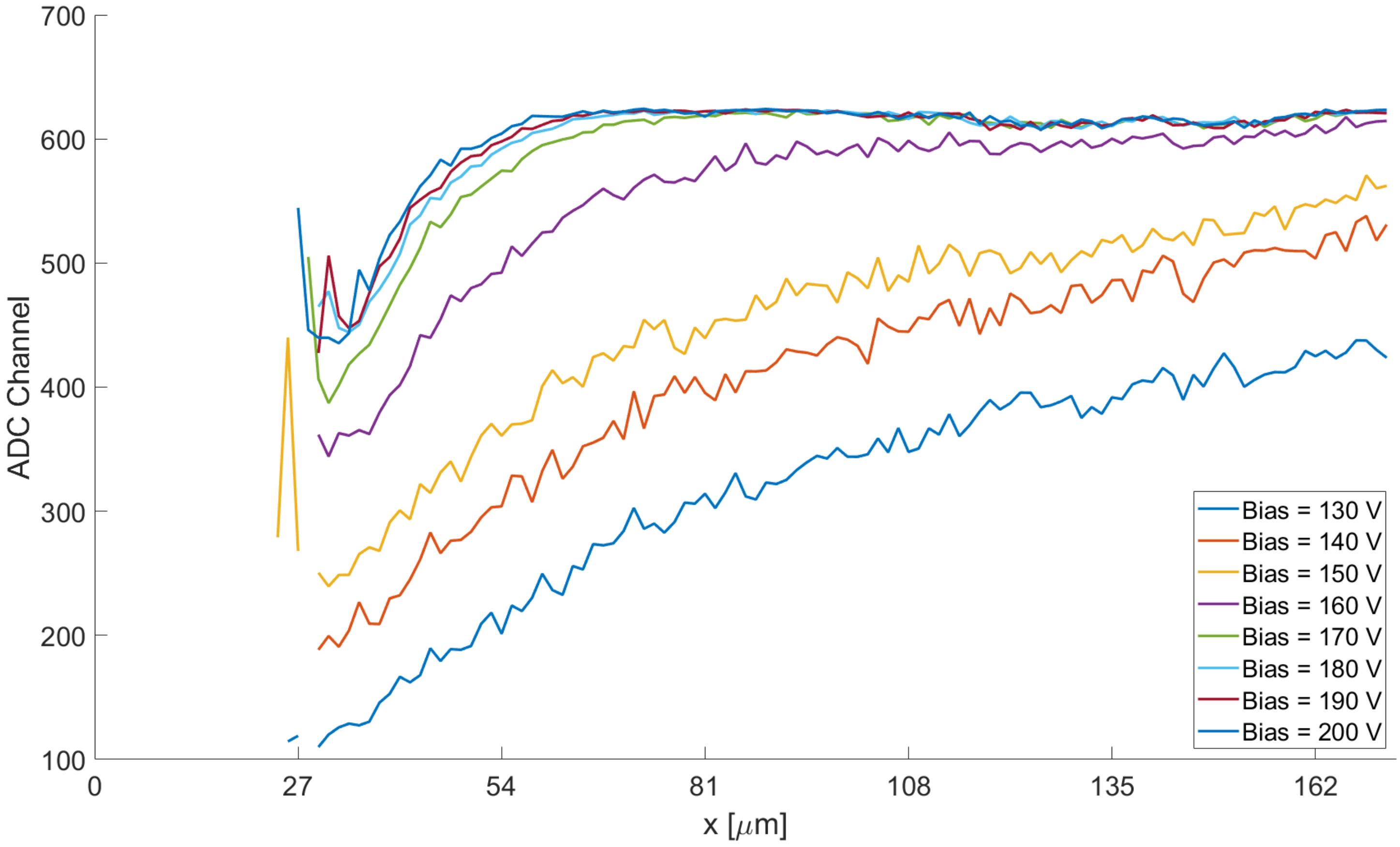
Bias Voltage variation from 130 V to 200 V

300 µm THICK SENSOR MAP RESULT

180 V

Considering the 25 µm pixel pitch on the 300 µm PM, increasing the bias voltage the same characteristics can be noticed.



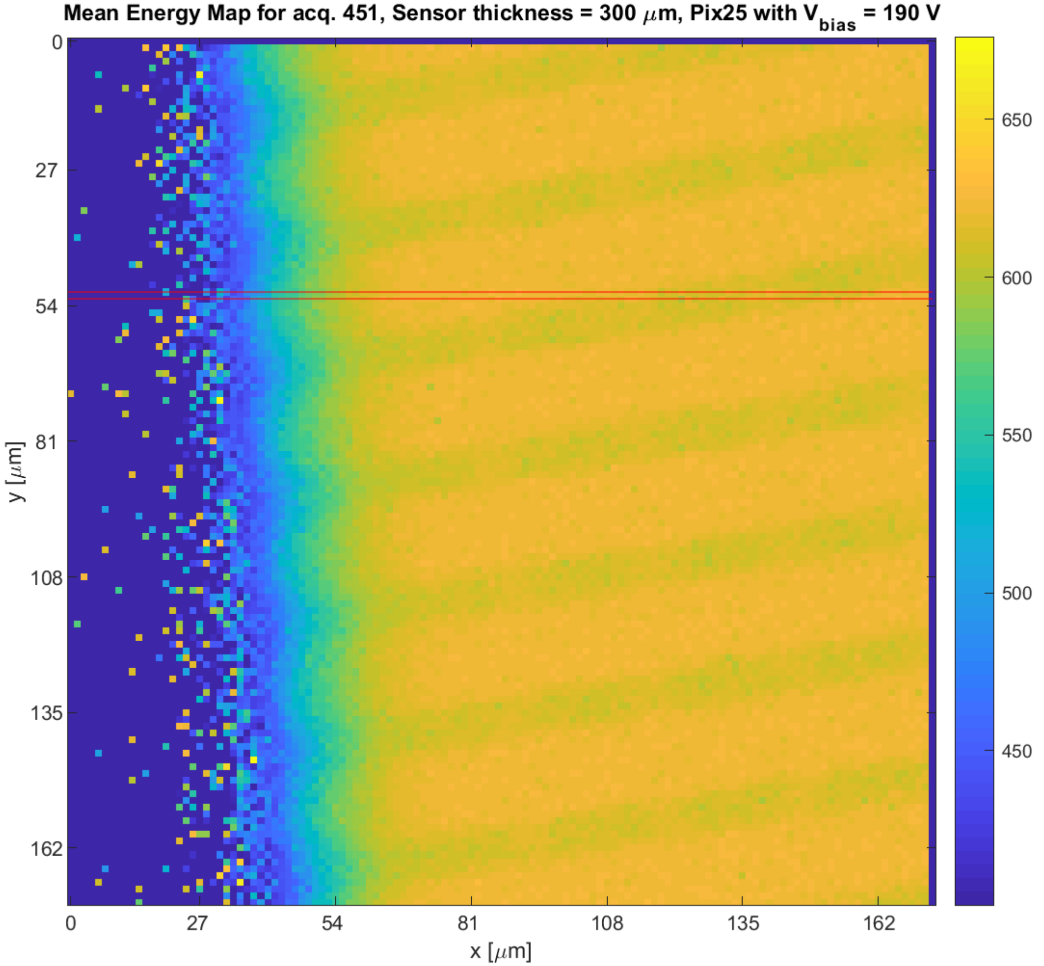


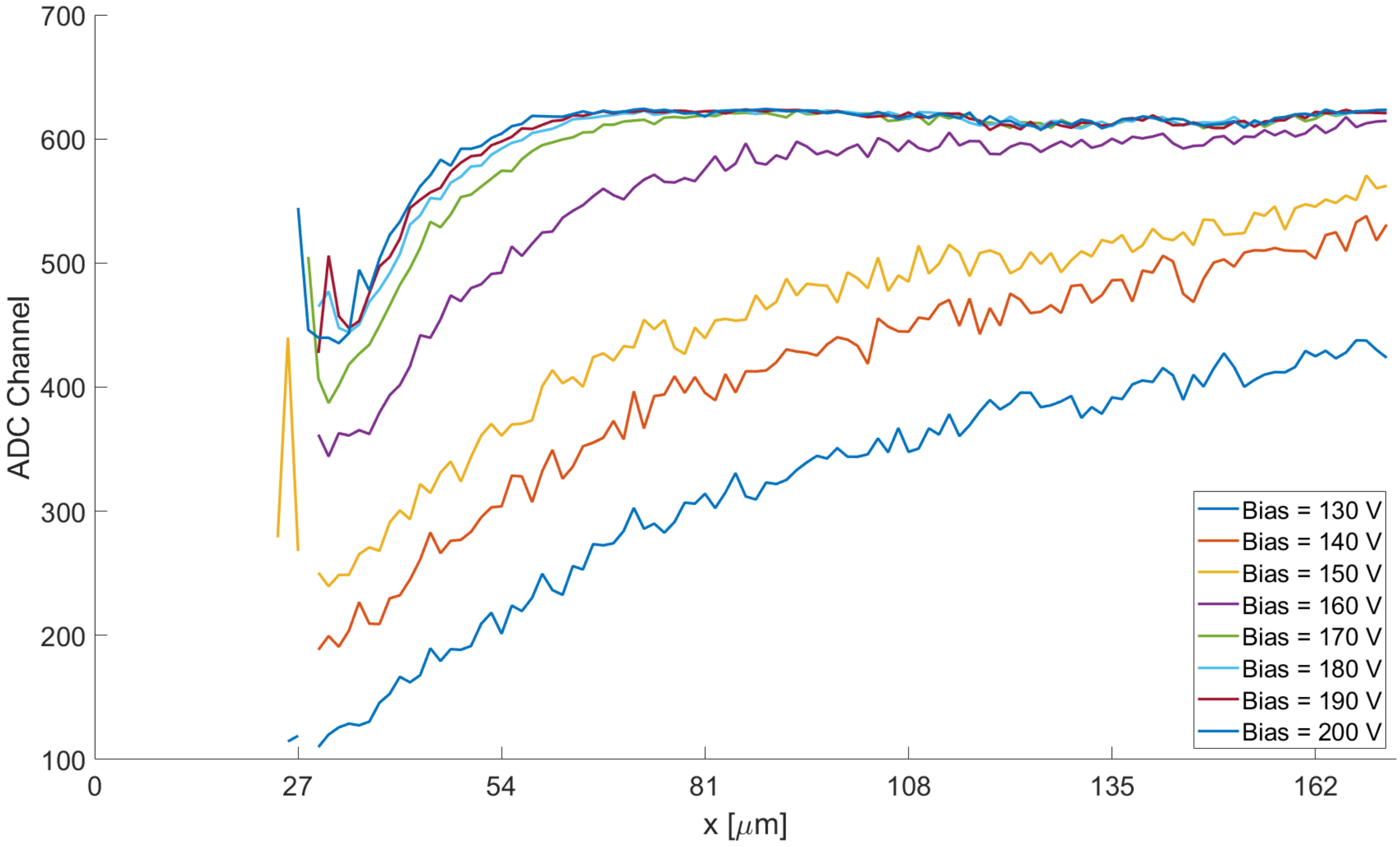
Bias Voltage variation from 130 V to 200 V

300 µm THICK SENSOR MAP RESULT

190 V

Considering the 25 µm pixel pitch on the 300 µm PM, increasing the bias voltage the same characteristics can be noticed.



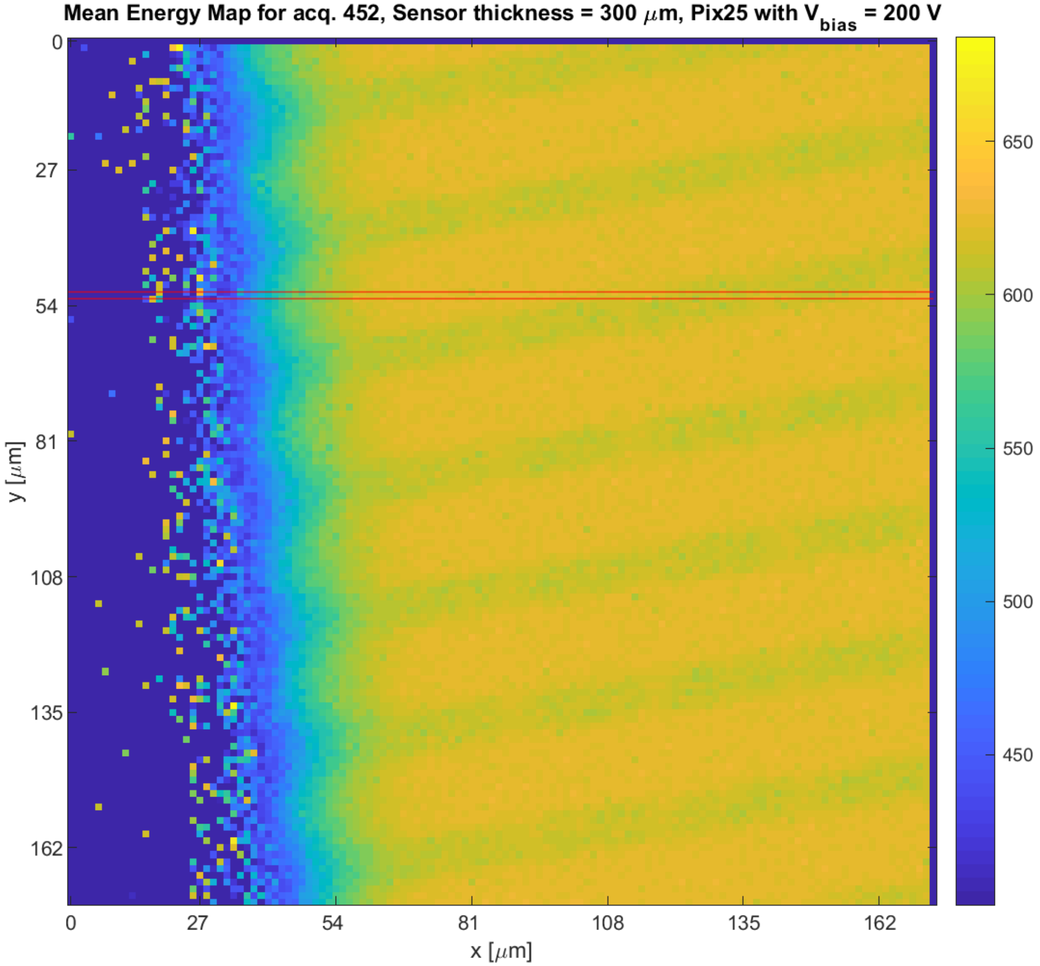


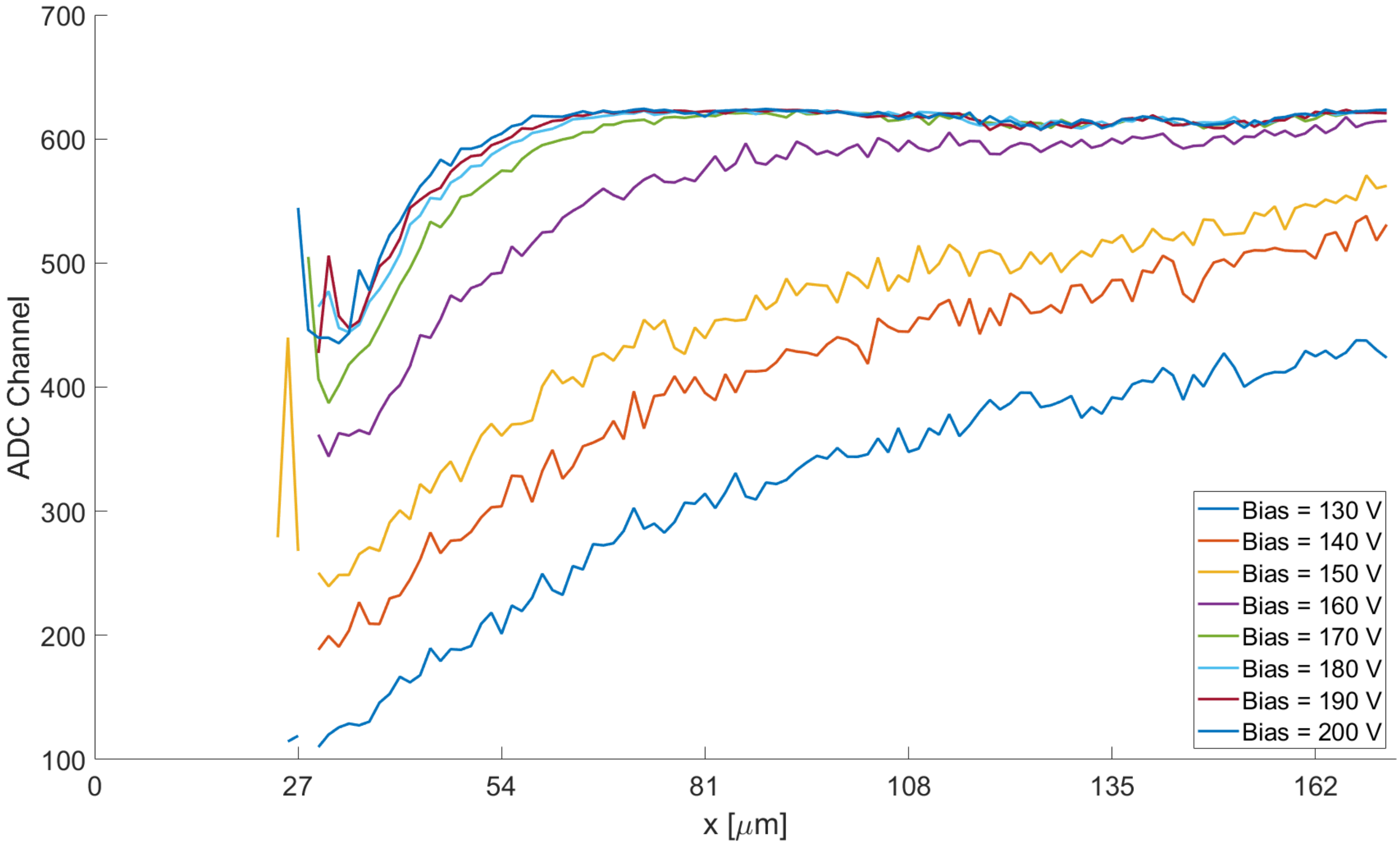
Bias Voltage variation from 130 V to 200 V

300 μm THICK SENSOR MAP RESULT

200 V

Considering the 25 μm pixel pitch on the 300 μm PM, increasing the bias voltage the same characteristics can be noticed.



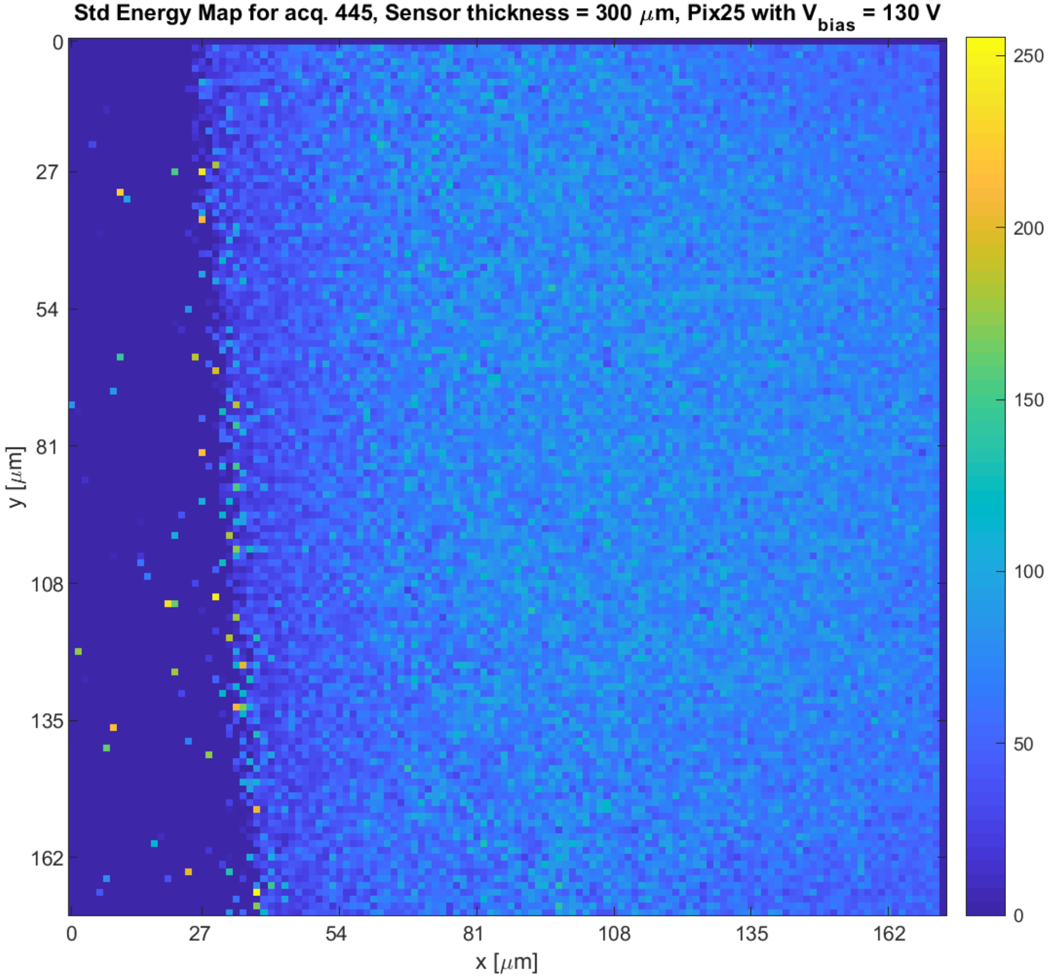


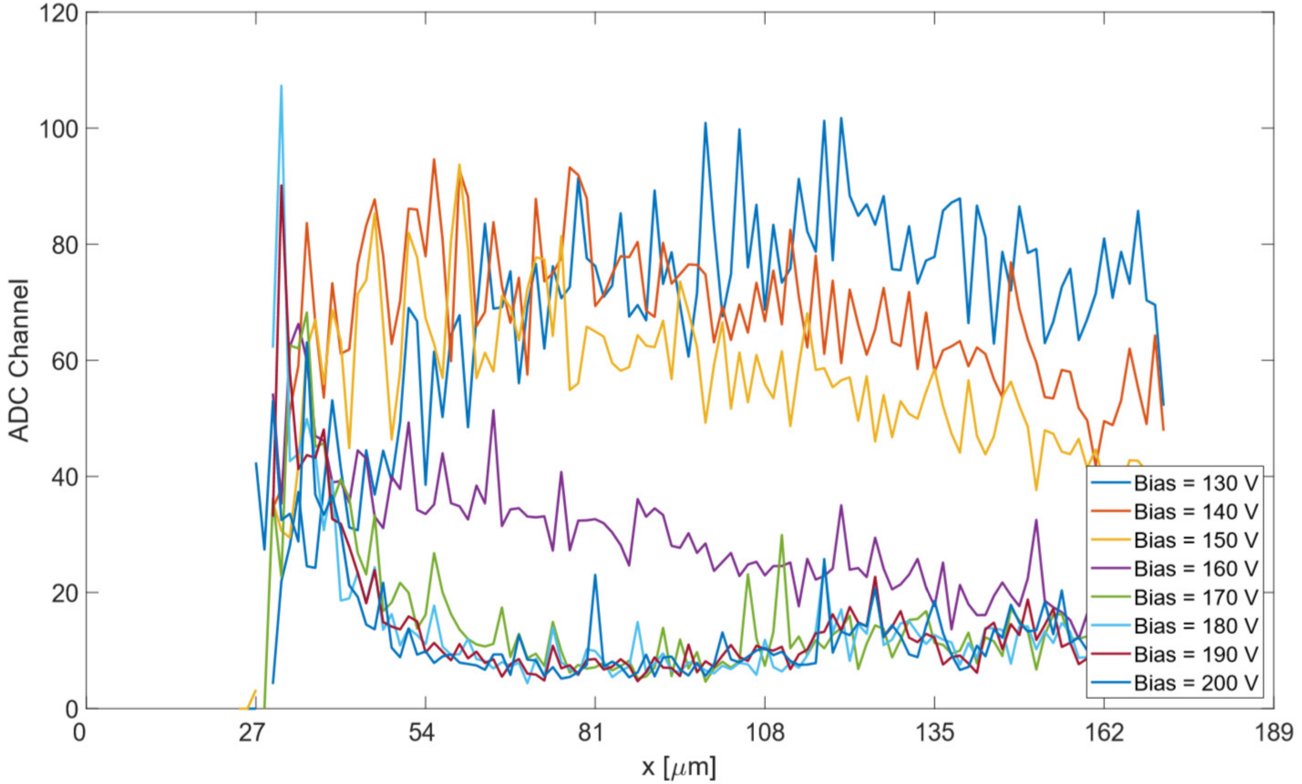
Bias Voltage variation from 130 V to 200 V

300 µm SENSOR CUT RESULT

On the other hand, horizontal cuts on the energy's standard deviation map with varying bias voltages conveys a more precise insight in the detector's electric field's distribution and uniformity:

130 V

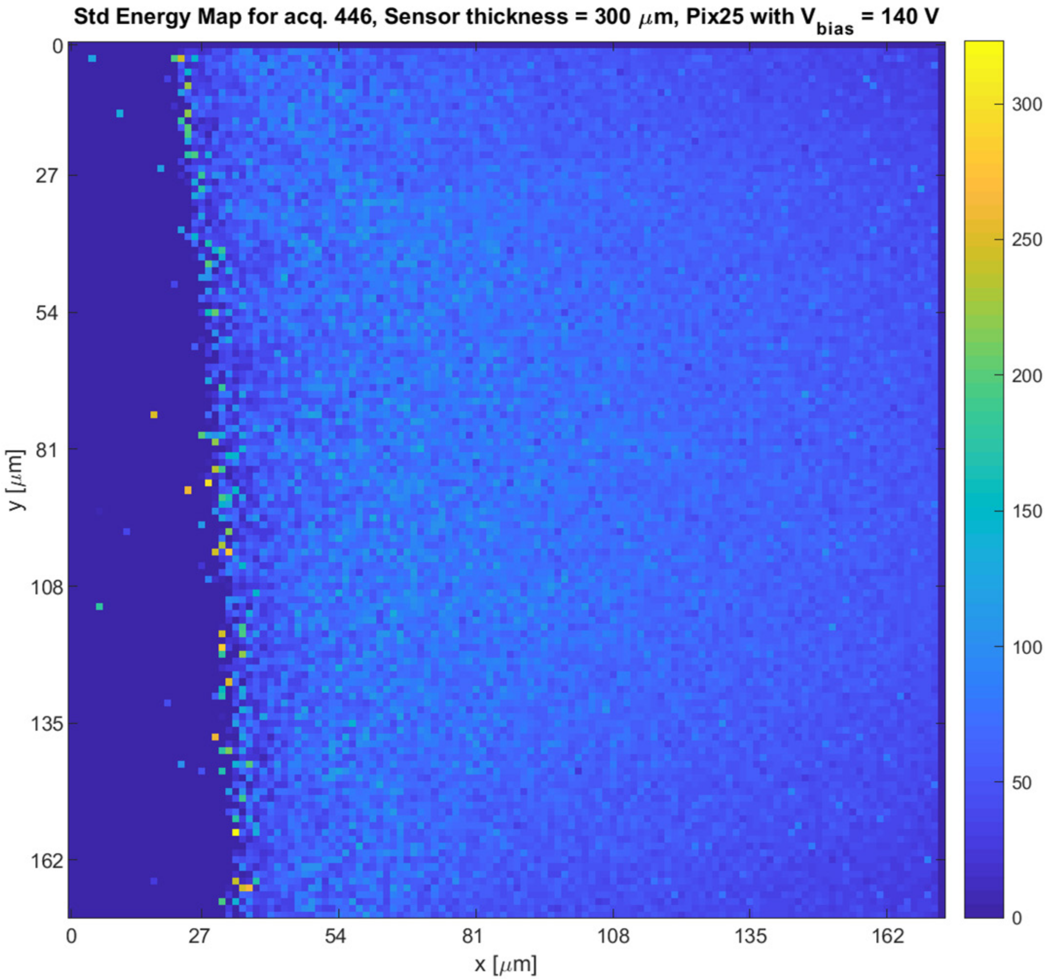


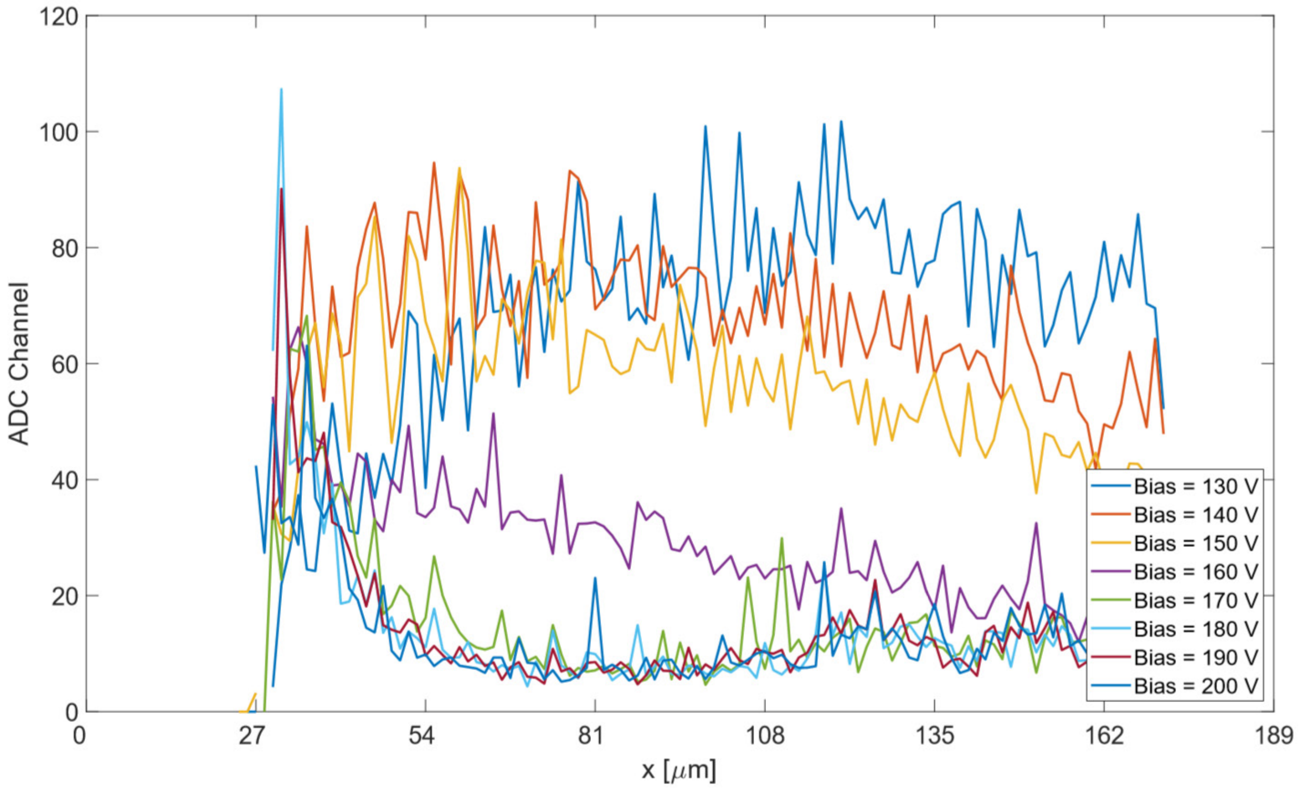


300 μm SENSOR CUT RESULT

On the other hand, horizontal cuts on the energy's standard deviation map with varying bias voltages conveys a more precise insight in the detector's electric field's distribution and uniformity:

140 V

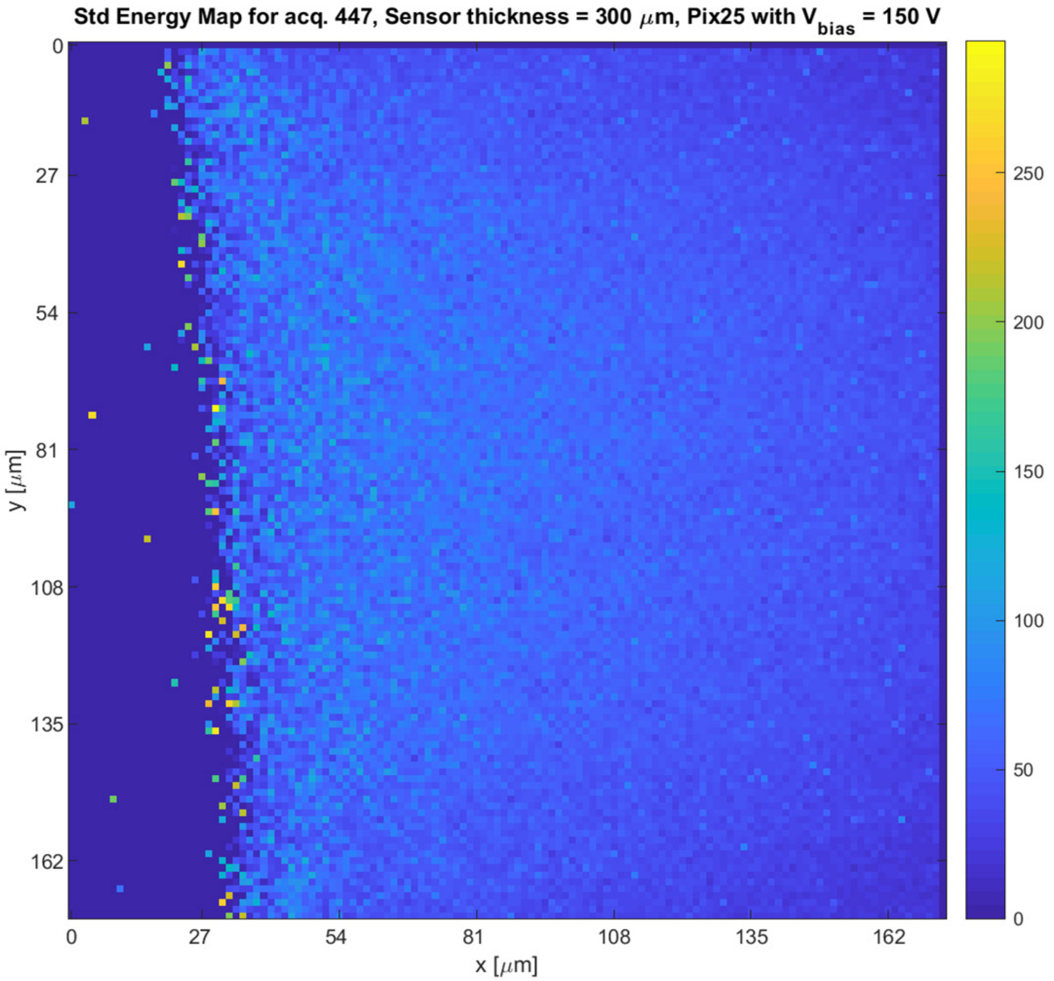


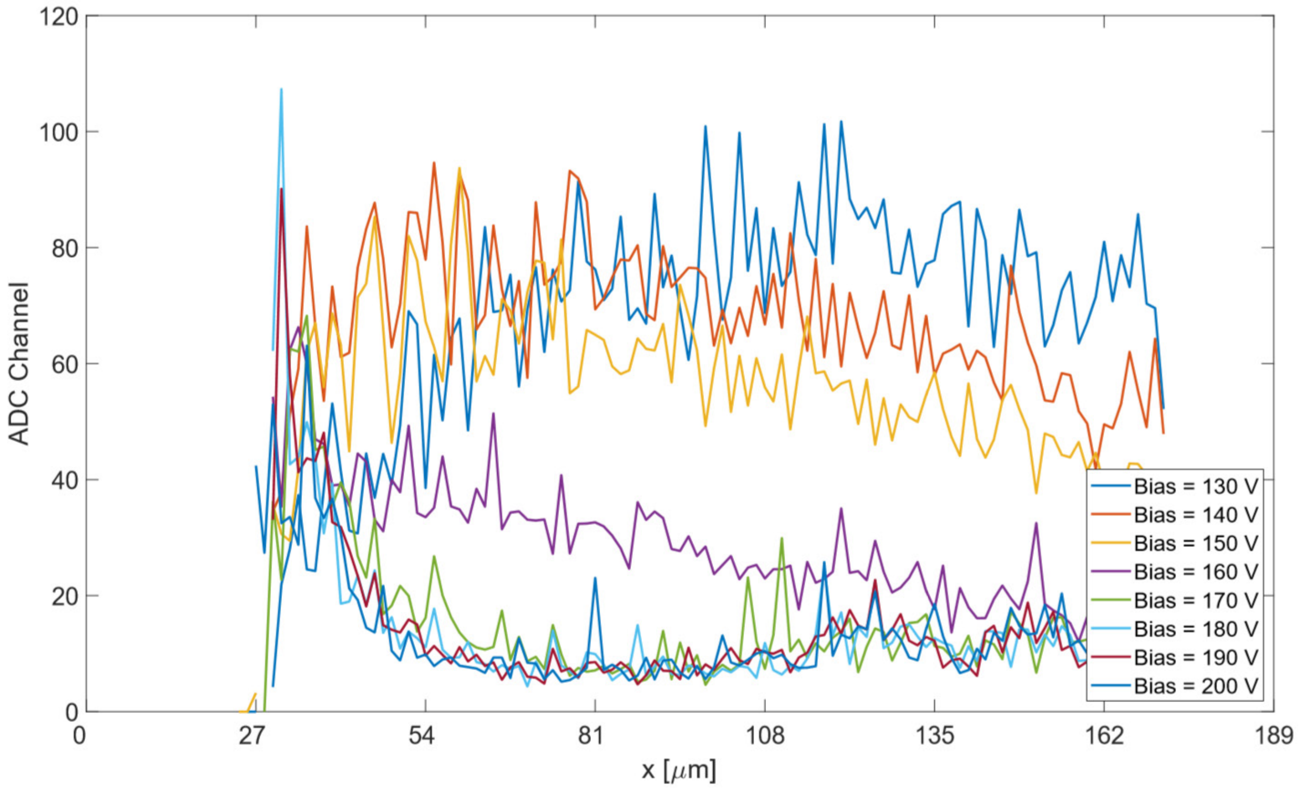


300 µm SENSOR CUT RESULT

On the other hand, horizontal cuts on the energy's standard deviation map with varying bias voltages conveys a more precise insight in the detector's electric field's distribution and uniformity:

150 V





300 µm SENSOR CUT RESULT

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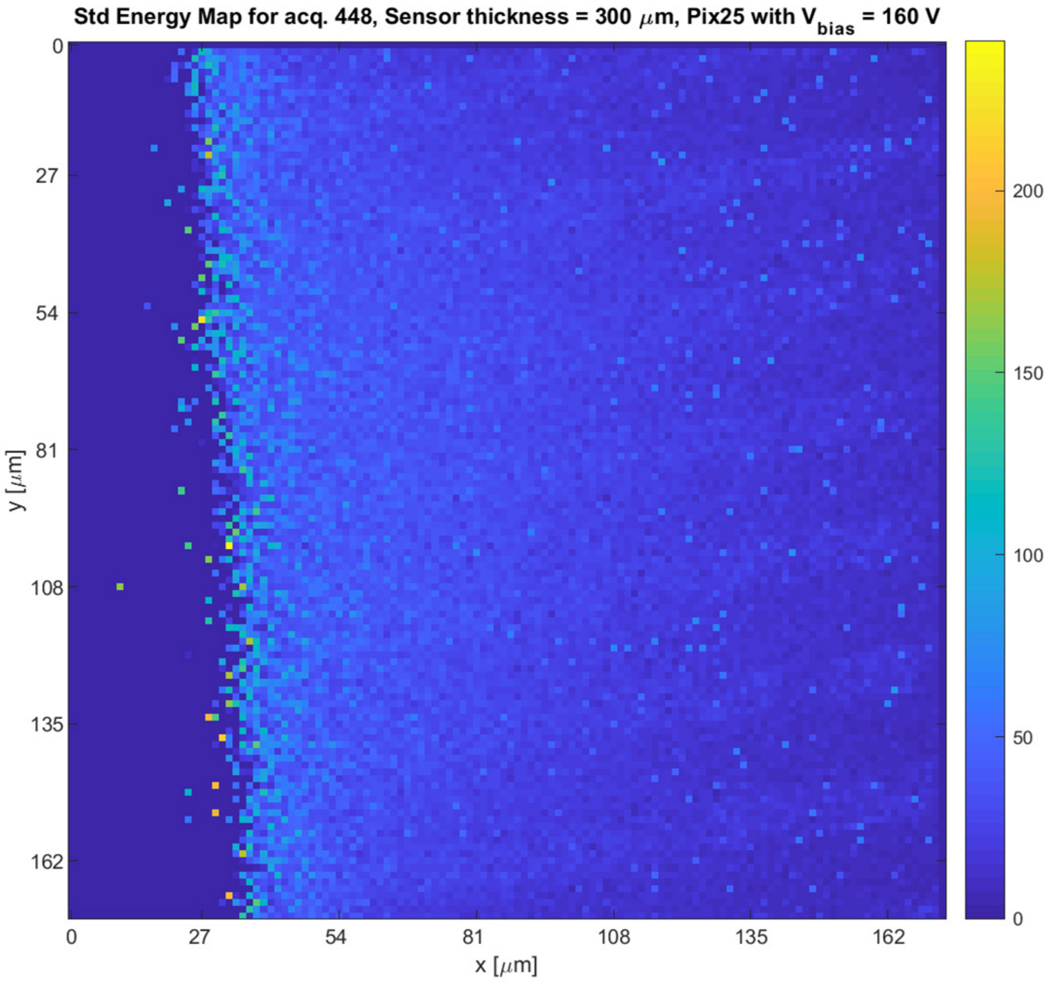
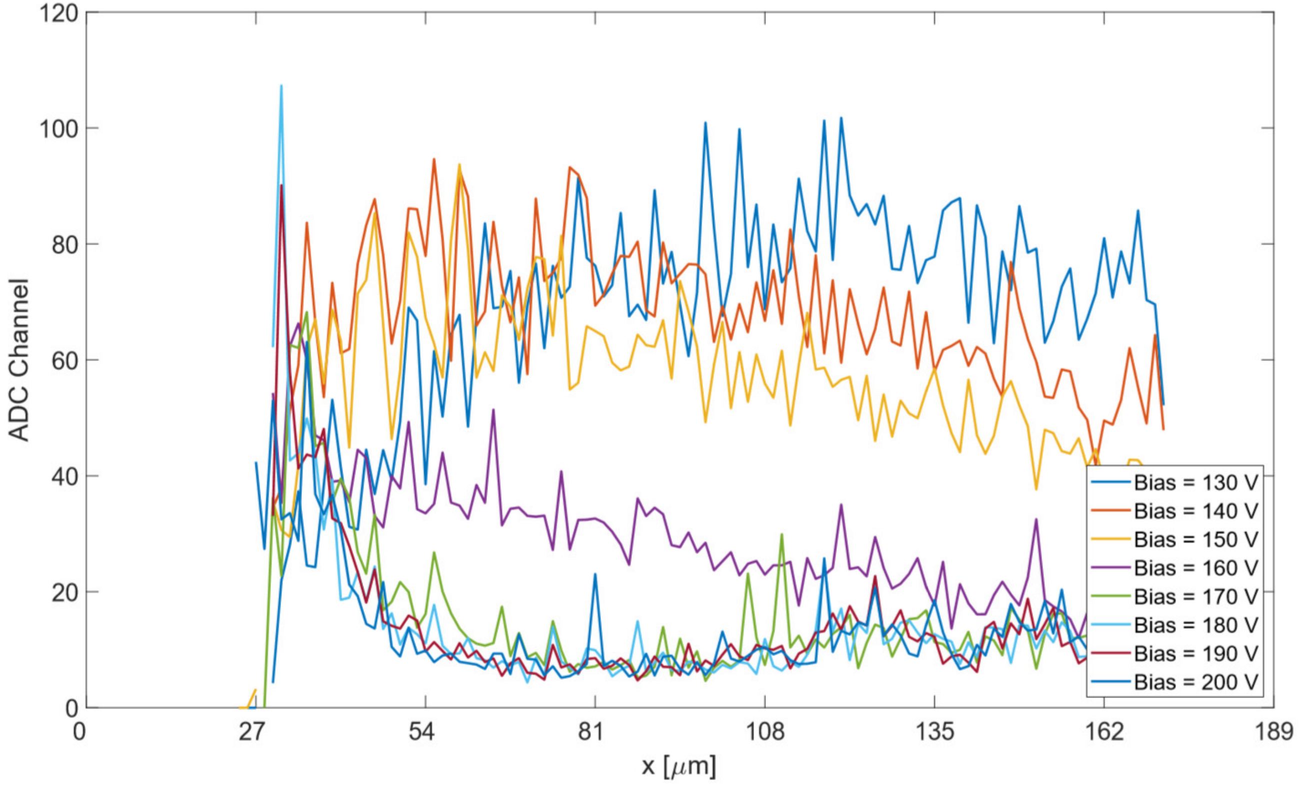
160 V

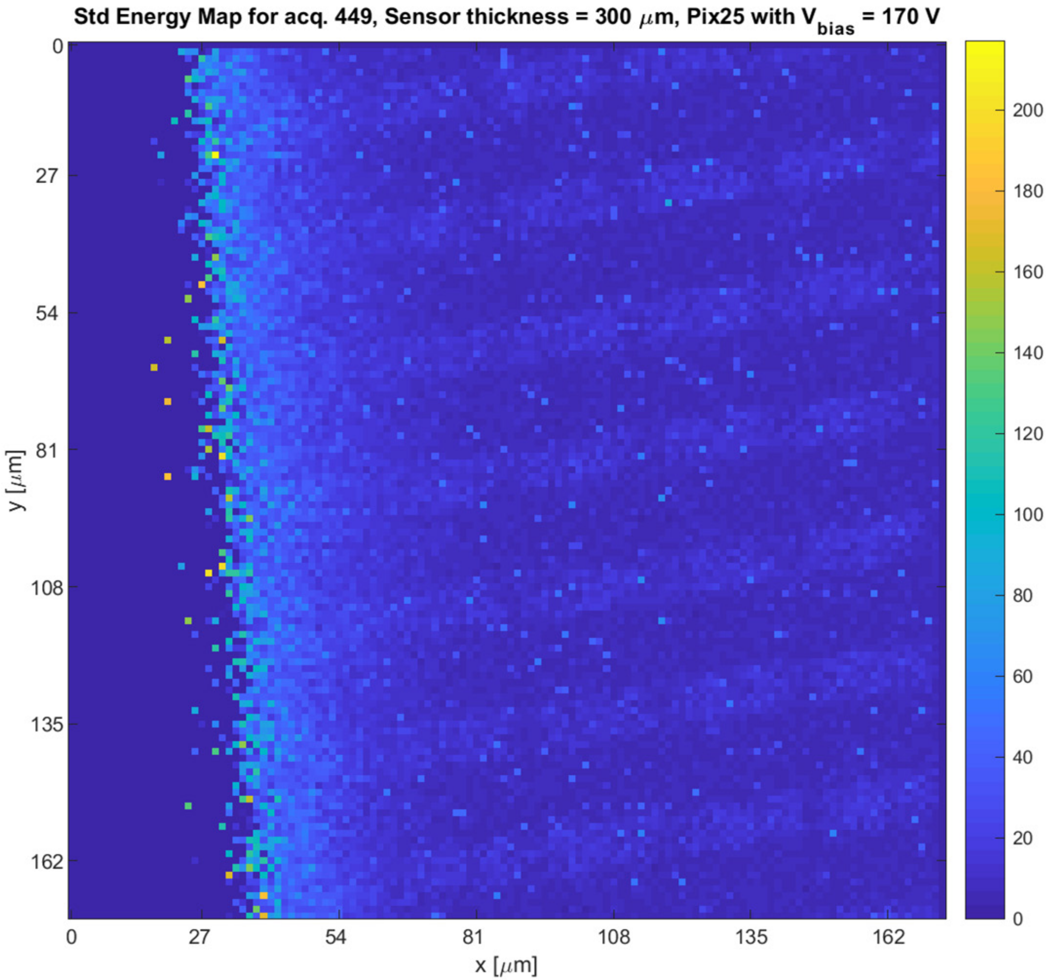


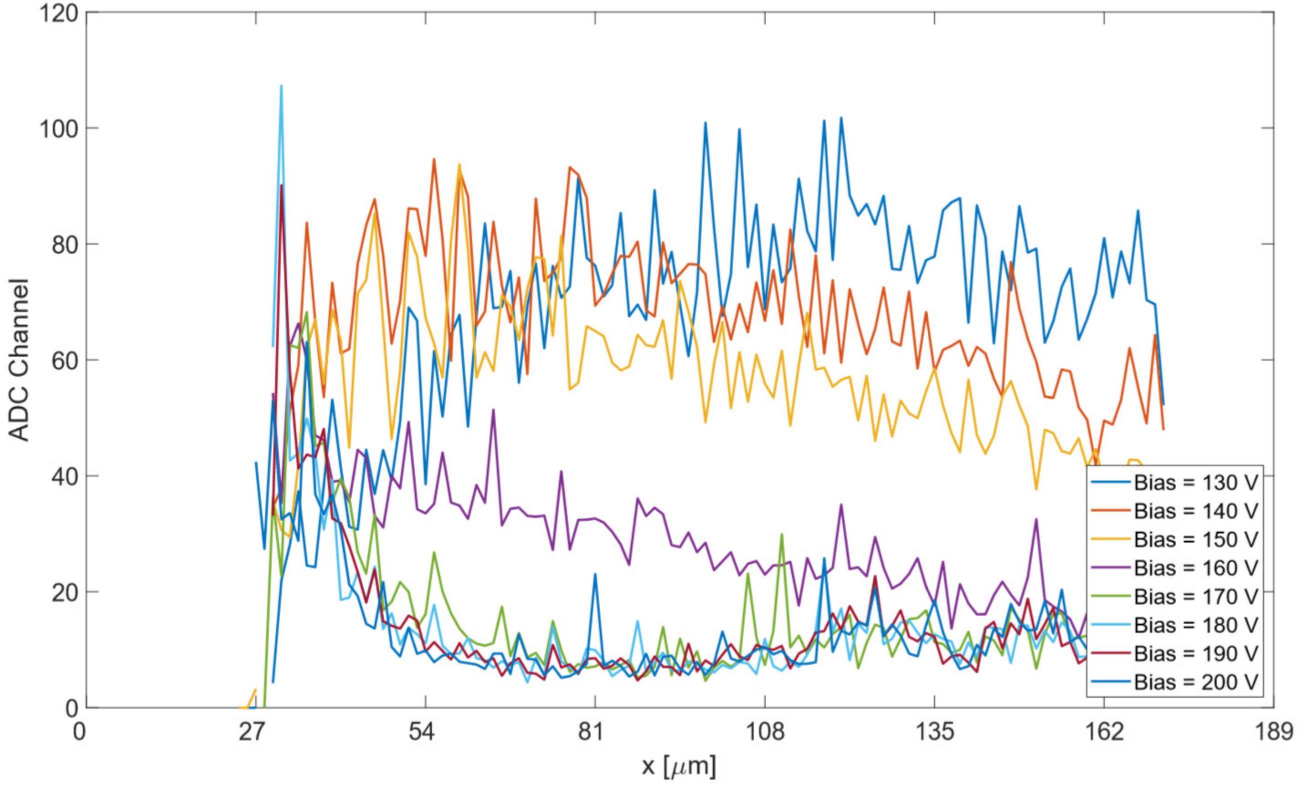


300 μm SENSOR CUT RESULT

On the other hand, horizontal cuts on the energy's standard deviation map with varying bias voltages conveys a more precise insight in the detector's electric field's distribution and uniformity:

170 V

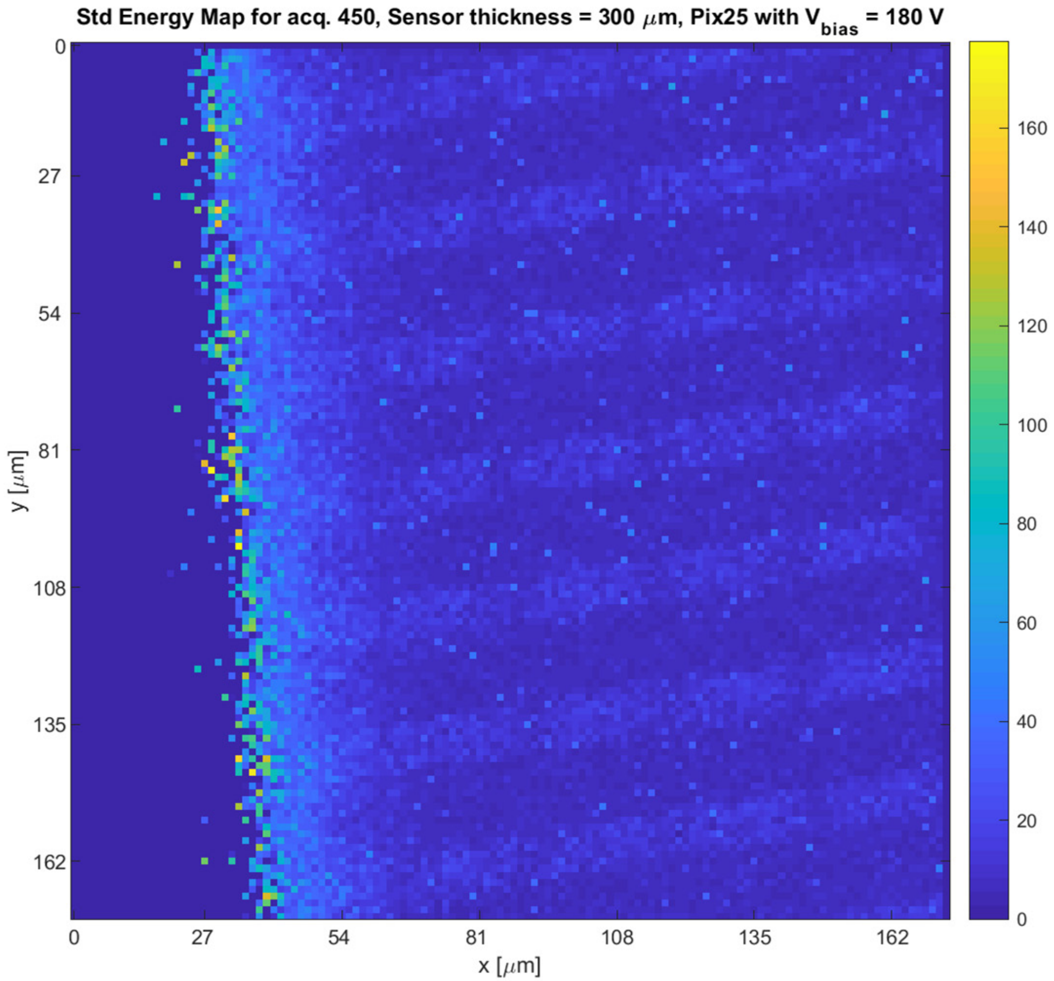


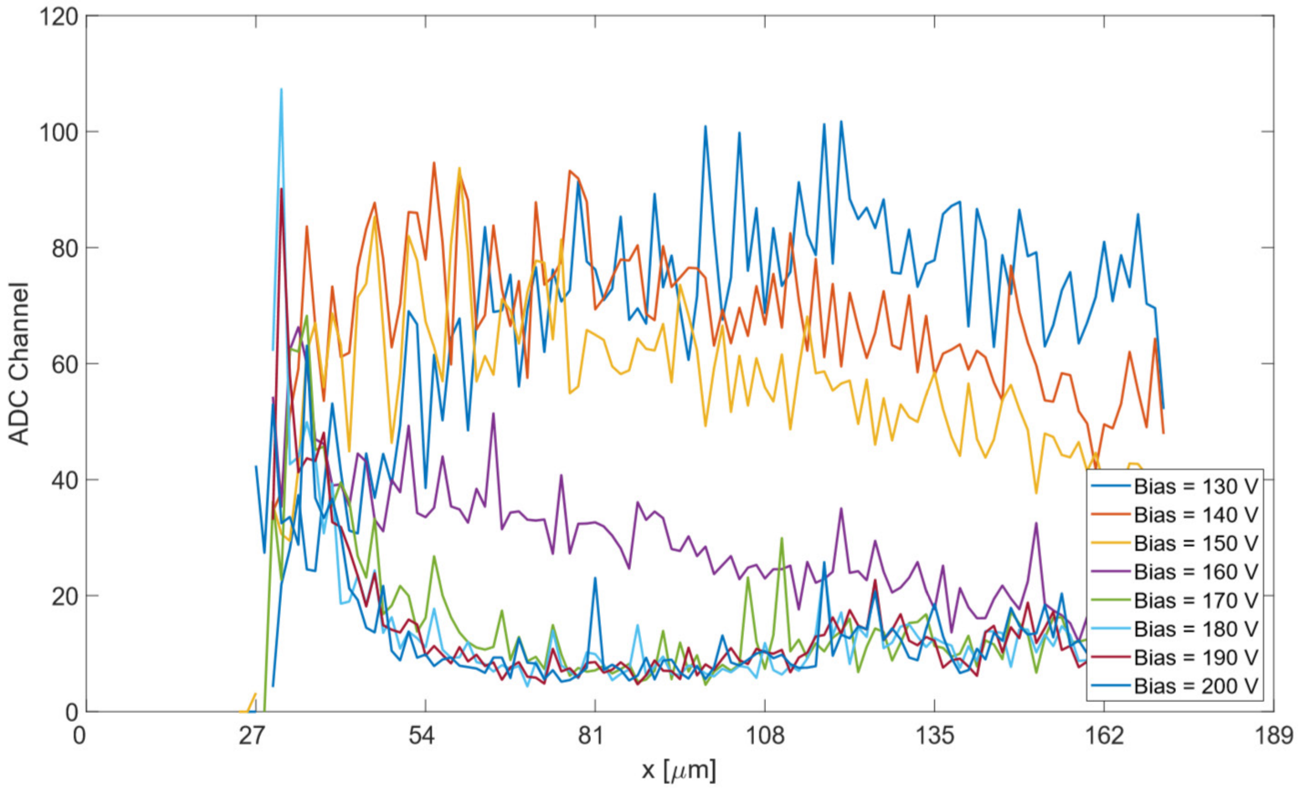


300 µm SENSOR CUT RESULT

On the other hand, horizontal cuts on the energy's standard deviation map with varying bias voltages conveys a more precise insight in the detector's electric field's distribution and uniformity:

180 V

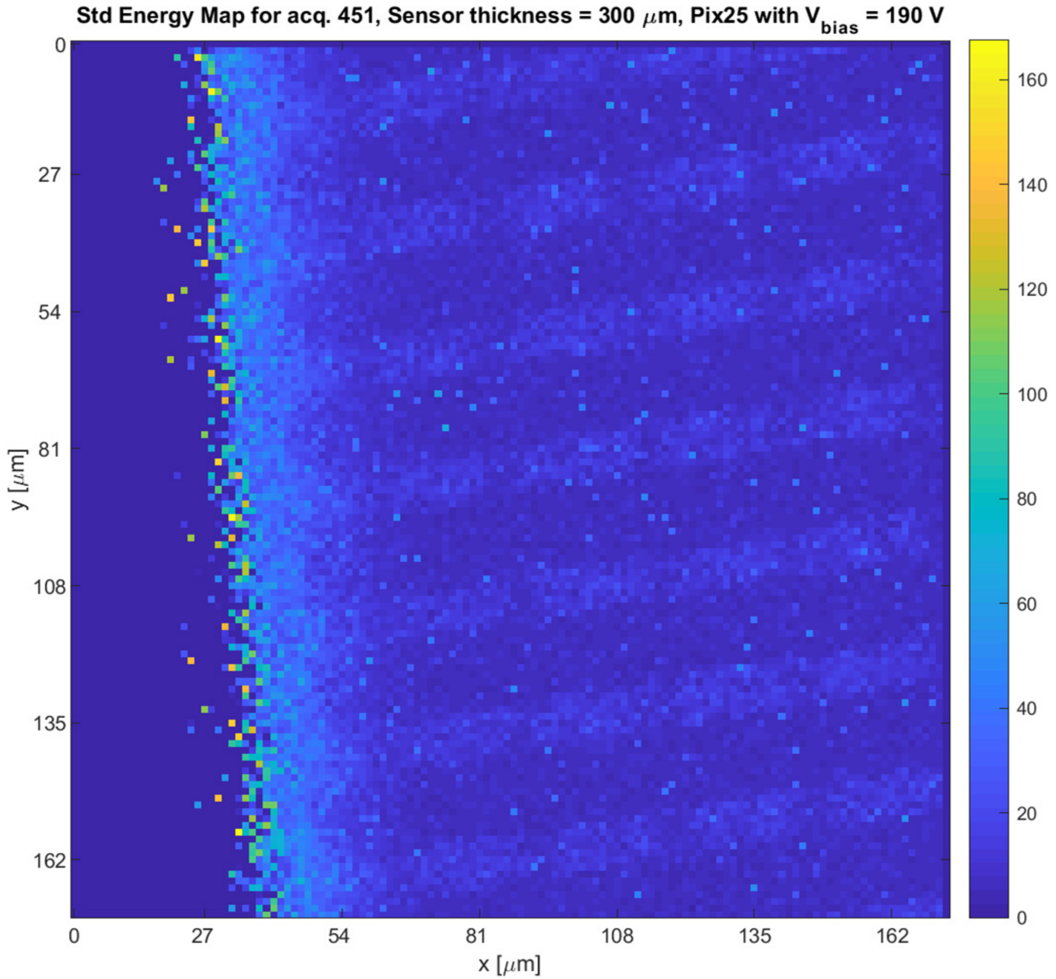


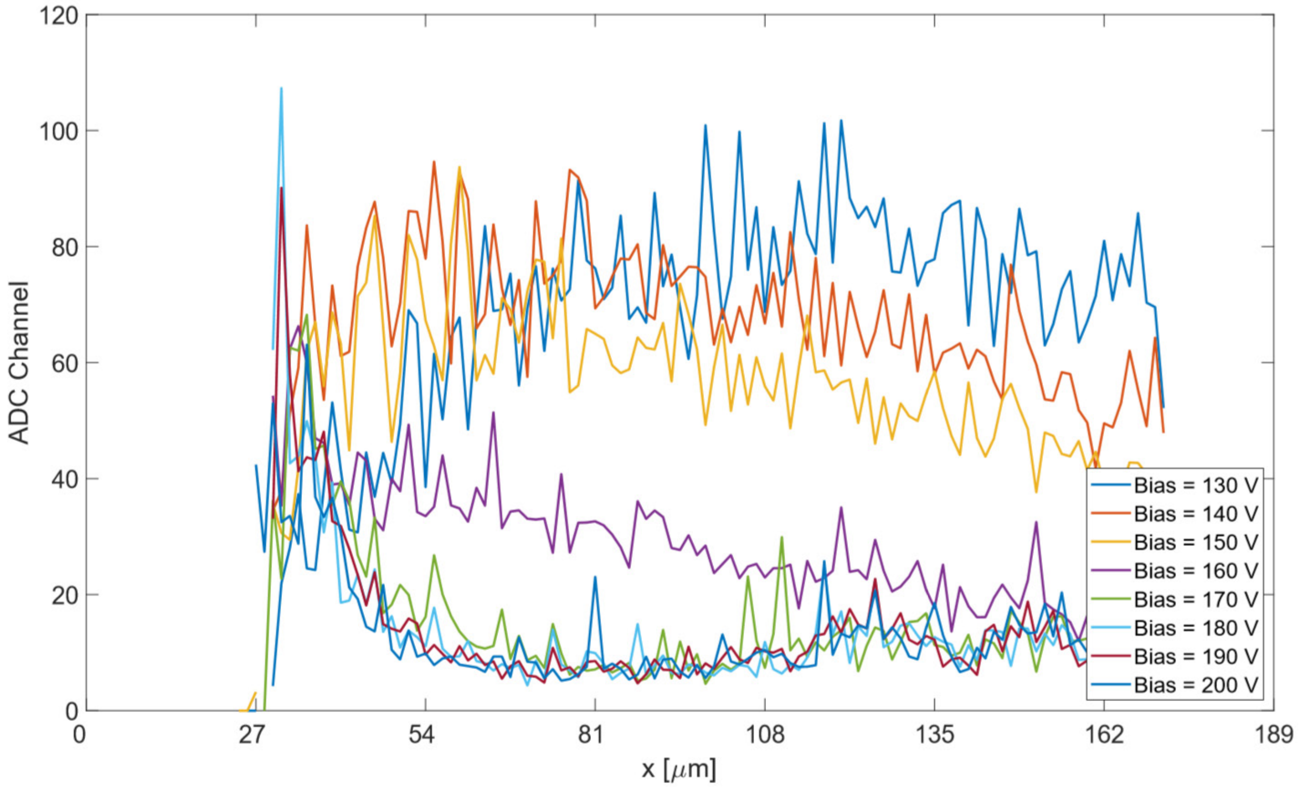


300 µm SENSOR CUT RESULT

On the other hand, horizontal cuts on the energy’s standard deviation map with varying bias voltages conveys a more precise insight in the detector’s electric field’s distribution and uniformity:

190 V

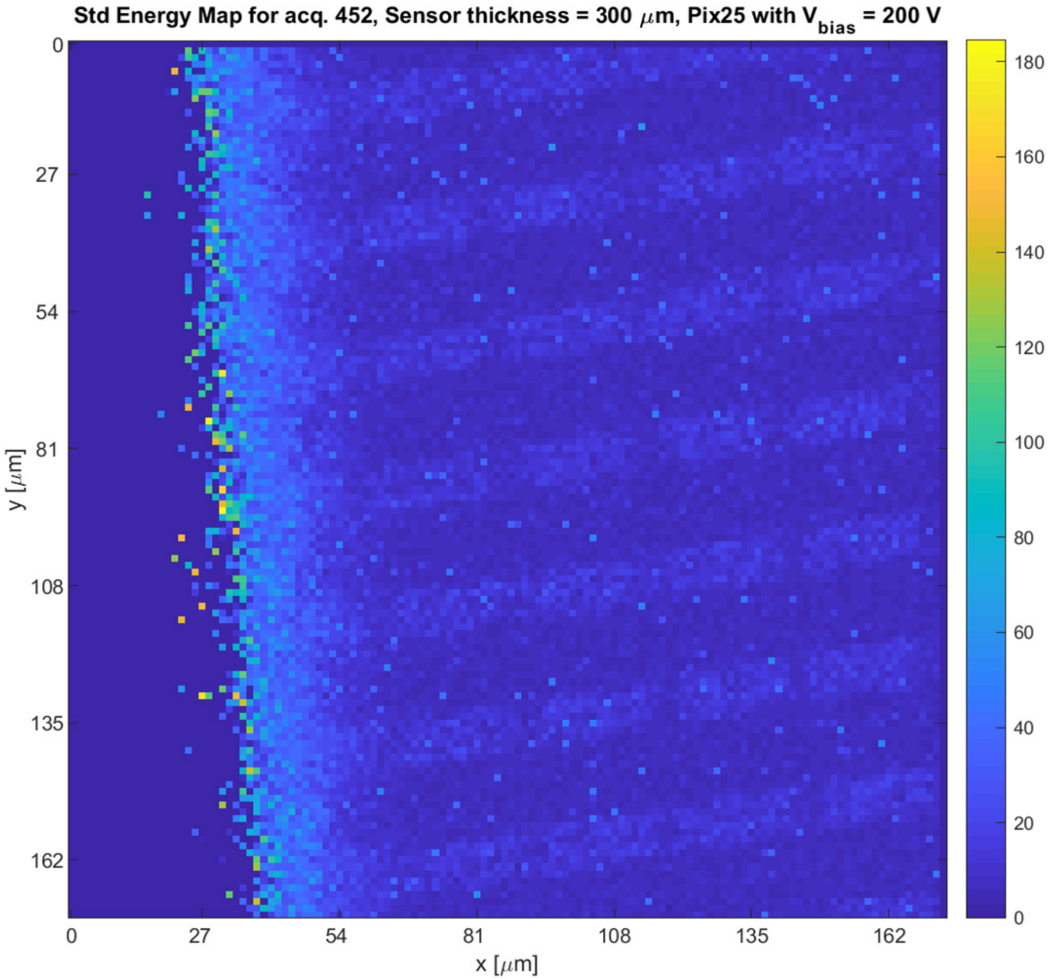


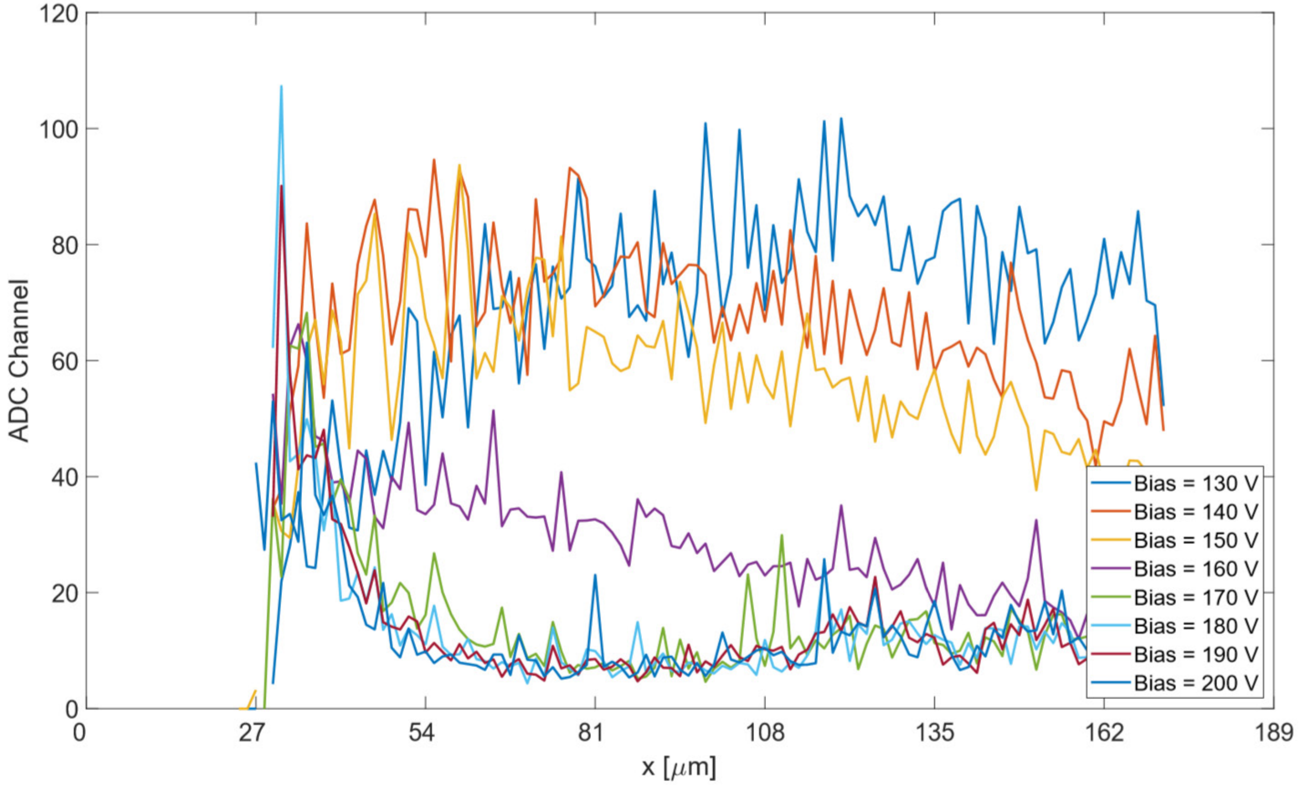


300 µm SENSOR CUT RESULT

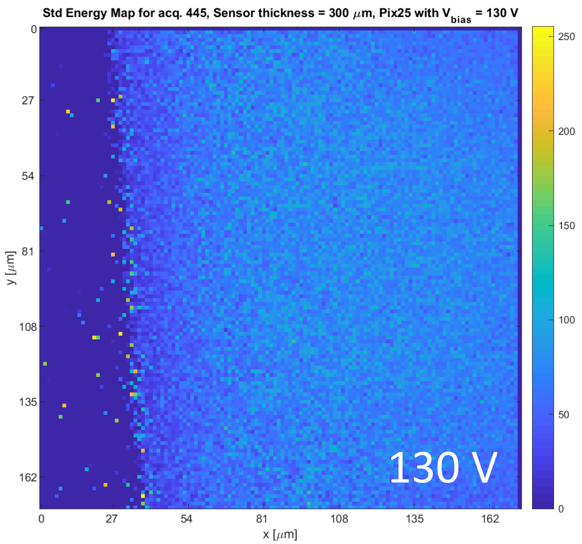
On the other hand, horizontal cuts on the energy's standard deviation map with varying bias voltages conveys a more precise insight in the detector's electric field's distribution and uniformity:

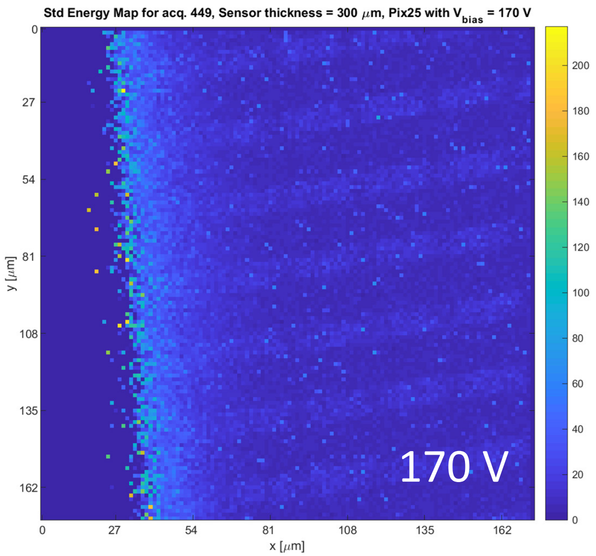
200 V

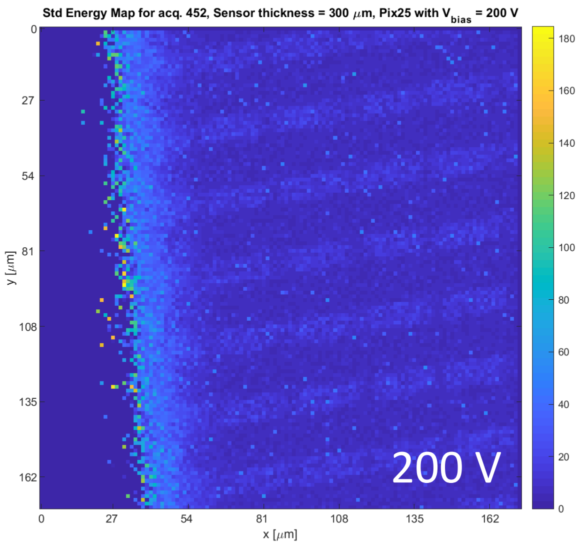




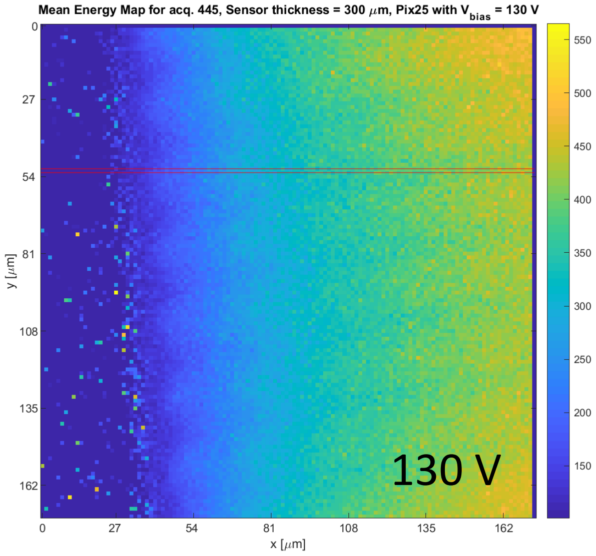
300 µm RESULT OVERVIEW

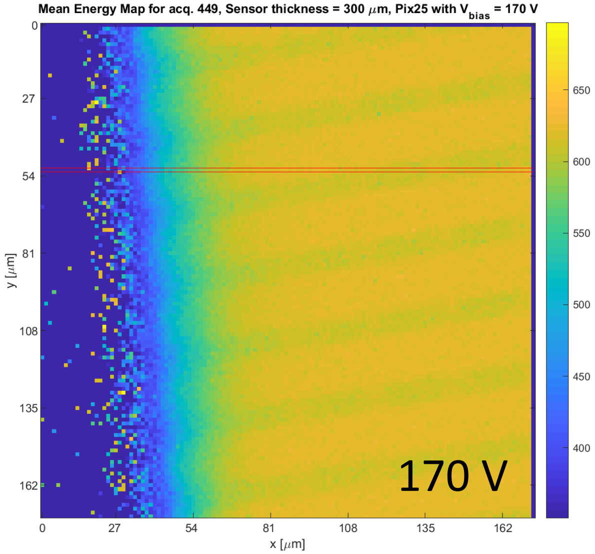


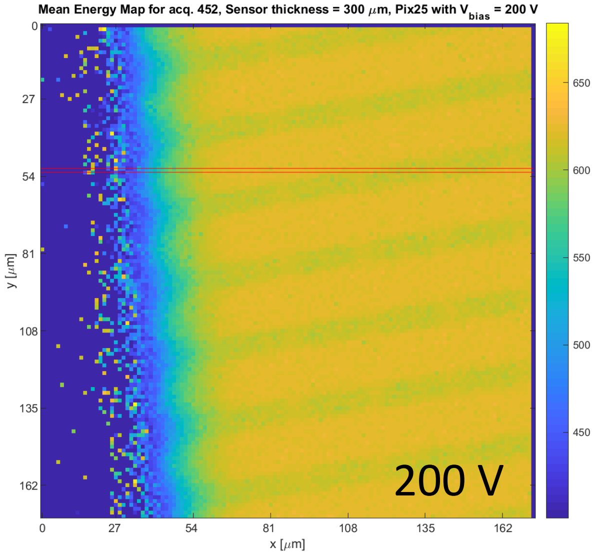




Bias Voltage







Standard deviation of the energy measurement in each pixel hit.

As per the 100 µm sensor, the under depleted sensor suffers from very high noise which disappears once the full depletion voltage is reached.

The full depletion voltage is slightly higher than expected.

BONUS TEST
300 µm

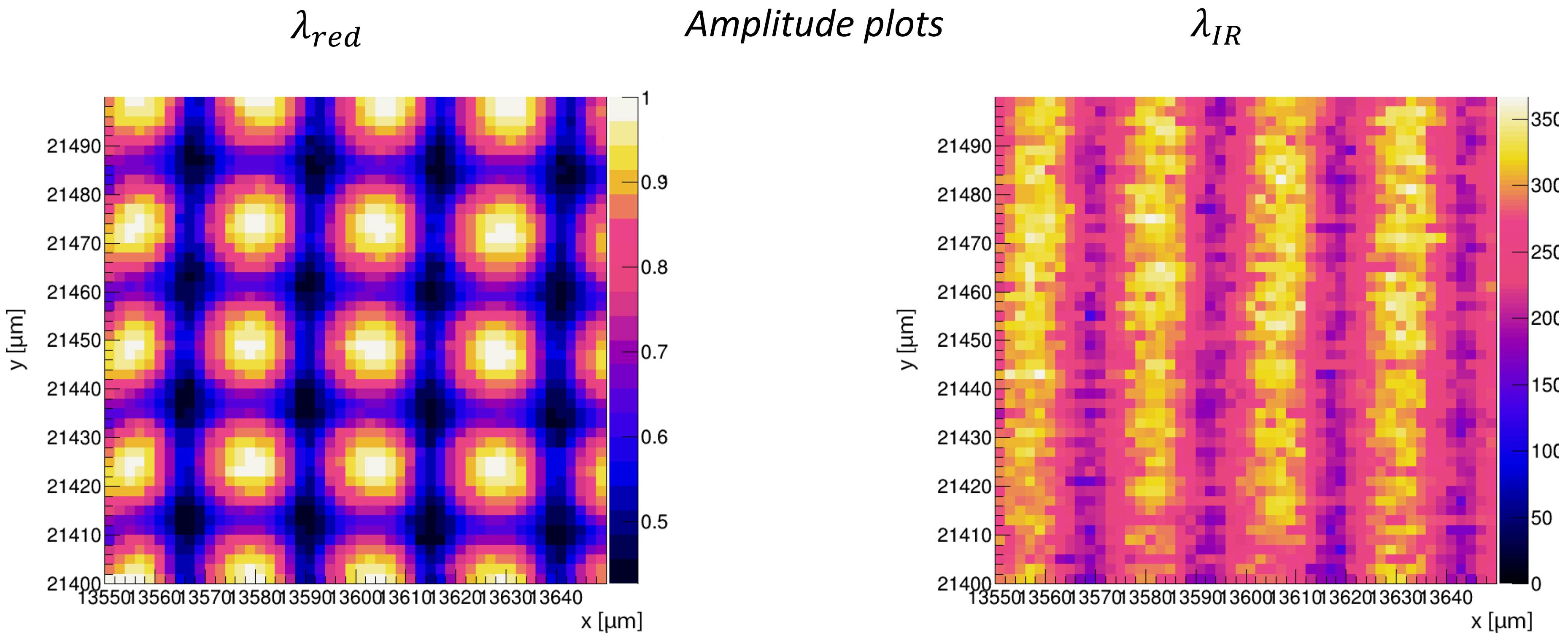
TCT SCAN ON 300 μm SENSOR

Two TCT (Transient Current Technique) scans were performed using different wavelengths:

- $\lambda_{red} = 660\,nm$ ⇒ superficial scan
- $\lambda_{IR} = 1064\,nm$ ⇒ whole thickness scan, similar to *mip* (about double the intensity for SNR reasons)

For each λ two maps are created, one of the *peak amplitude* and one of the *charge collection efficiency* using a 2 μm step:

Amplitude plots



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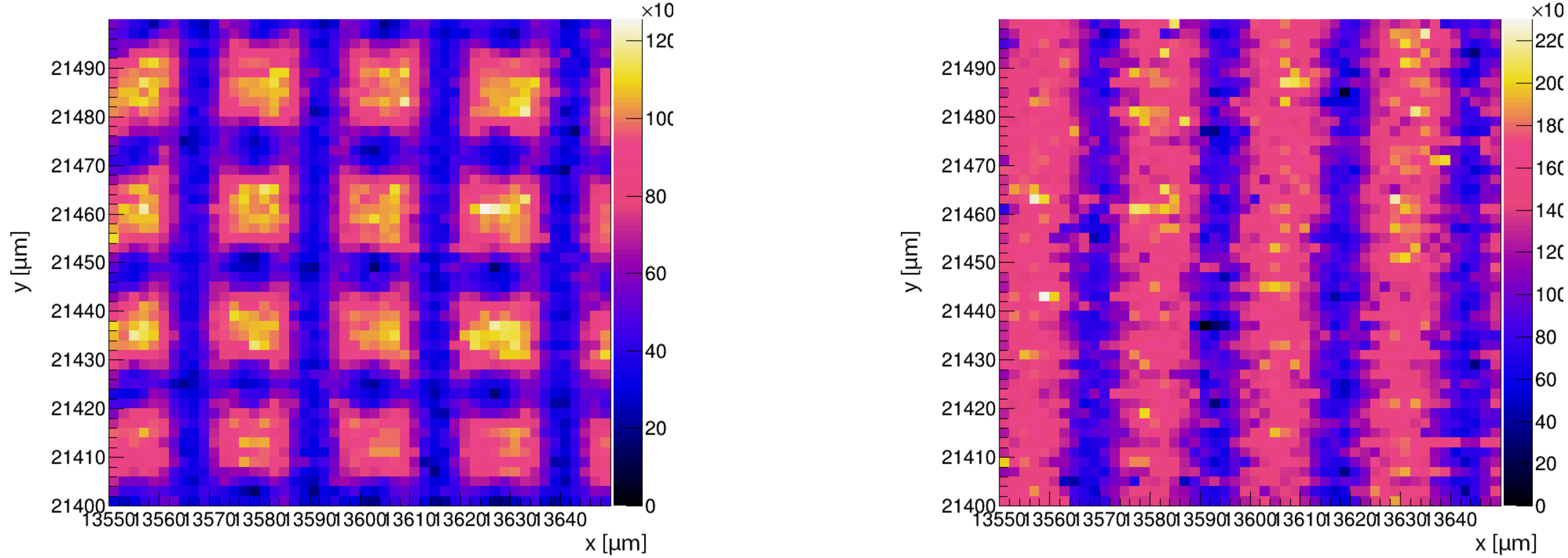
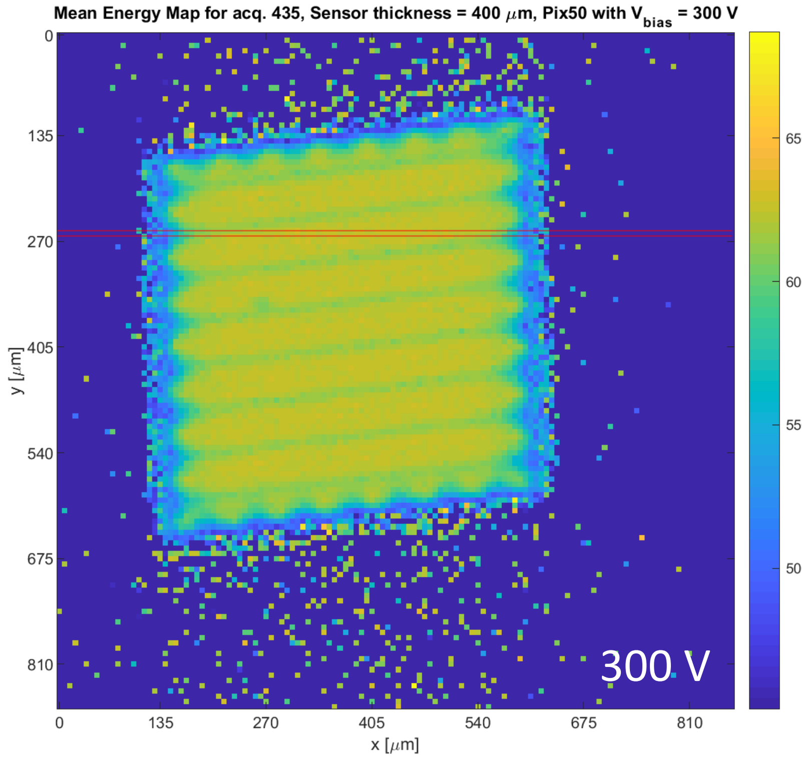
For each λ two maps are created, one of the *peak amplitude* and
one of the *charge collection efficiency* using a 2 µm step:

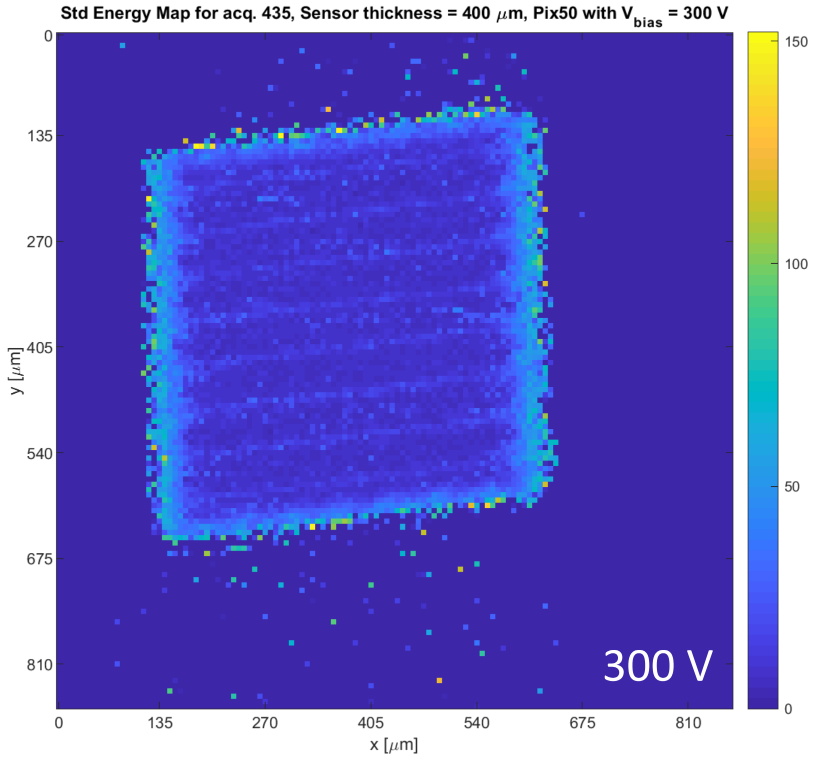
λ_{red} *CCE plots* λ_{IR}

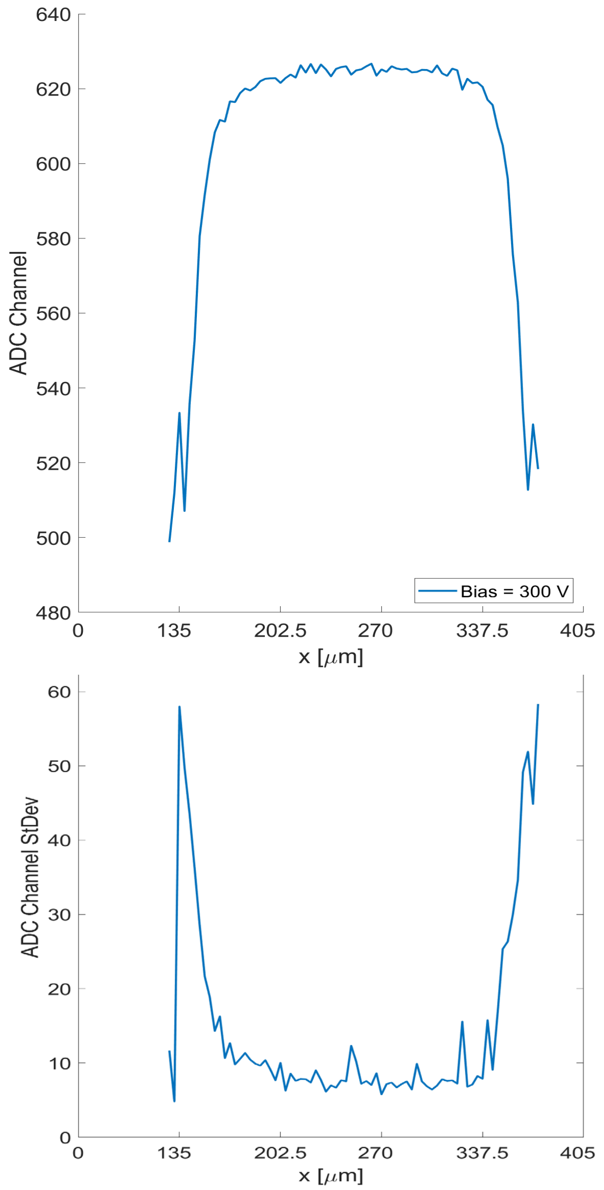


400 µm

400 μm THICK SENSOR MAP RESULT


Mean Energy Map for acq. 435, Sensor thickness = 400 μm, Pix50 with V_{bias} = 300 V

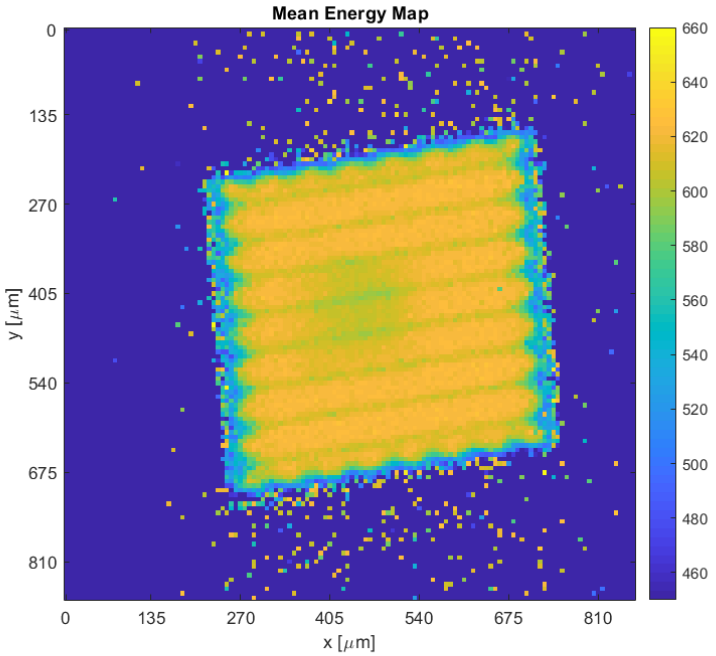

Std Energy Map for acq. 435, Sensor thickness = 400 μm, Pix50 with V_{bias} = 300 V



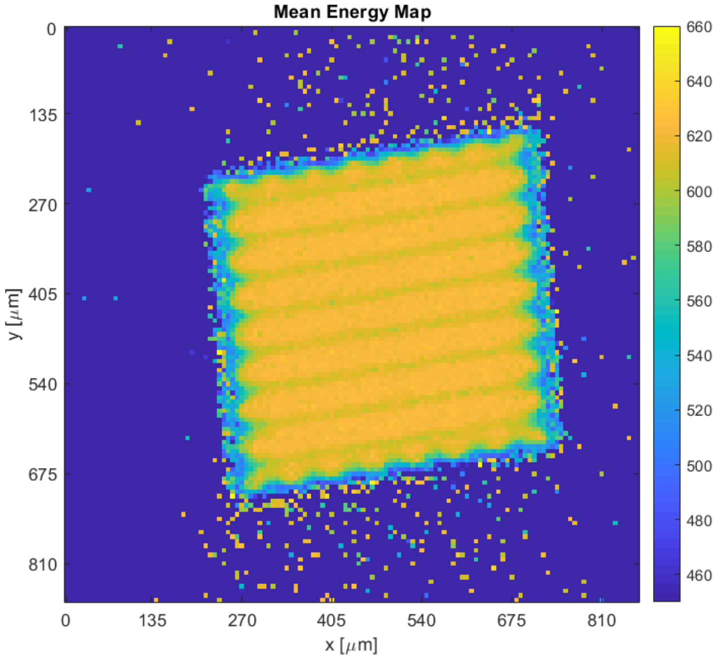
PRELIMINARY CURIOSITY – CCE RECOVERY

An interesting result has been the refresh of the CCE via an increase of the V_{HV} after long exposures to the beam. In fact, when at a low fully depleted voltage, the proton's "damage" is slightly visible after a scan longer than an hour in the same confined location. An Increase in V_{HV} has then made the lowered CCE effect disappear.

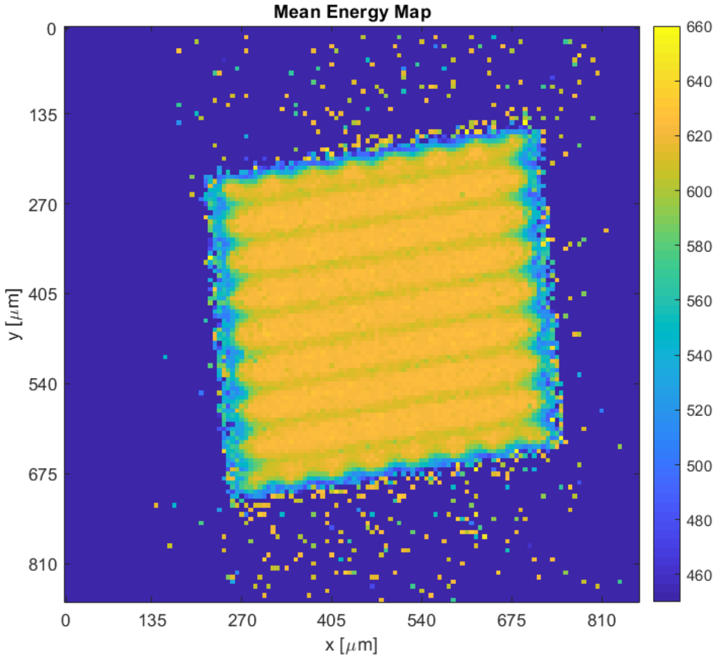
150 V



200 V



240 V



RECAP

- ○ Very good uniformity in CCE throughout the matrix
- ○ Sharp electric field edges above V_{fd}

PRELIMINARY RESULTS:

- ○ An about 2.7 % attenuation has been measured on the metal lines, very close to the preliminary simulated 3.5%
- ○ Radiation induced CCE reduction can be prevented/reduced by increasing the depletion voltage

Thickness [µm]	$V_{fd,th}$	V_{fd}	$V_{compliance}$
100	50	40	70
300	150	170	250
400	200	200	210

Thank you, *Raffaele Aaron Giampaolo*

INFN Zagreb field team:
Caccia Massimo
Giampaolo Raffaele Aaron
Mattiazzo Serena
Santoro Romualdo

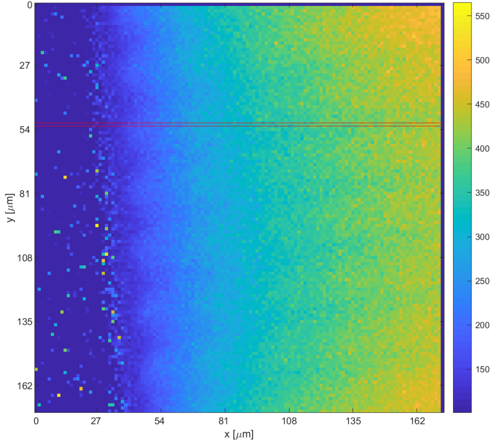
INFN team that supervised from Italy:
Croci Tommaso
Da Rocha Rolo Manuel
Di Salvo Andrea
Mandurrino Marco
Olave Jonhatan
Pancheri Lucio
Tosello Flavio

Thank you to all our IRB colleagues:
Valery, Milko, Matti, Aneliya, Andreo, George, Milan and all the others whose names I don’t know how to spell ☺

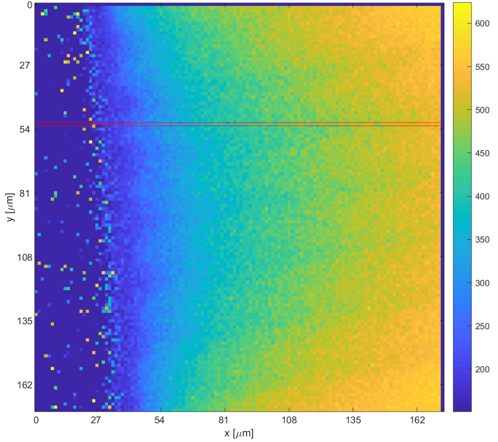
BACKUP

300 µm SENSOR MAP OVERVIEW

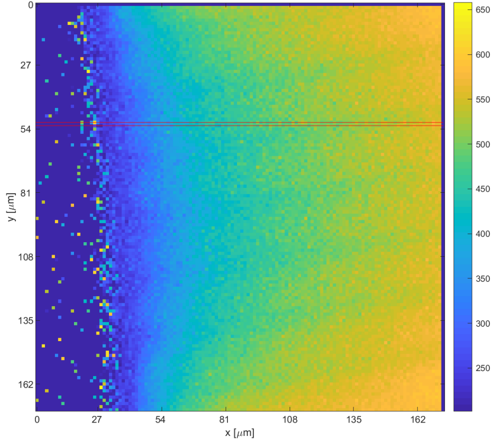
Mean Energy Map for acq. 445, Sensor thickness = 300 μm, Pix25 with V_{bias} = 130 V



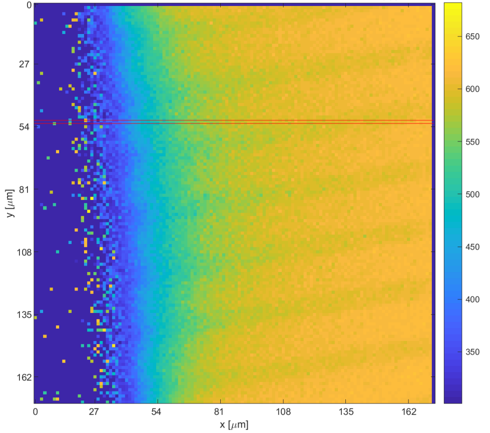
Mean Energy Map for acq. 446, Sensor thickness = 300 μm, Pix25 with V_{bias} = 140 V



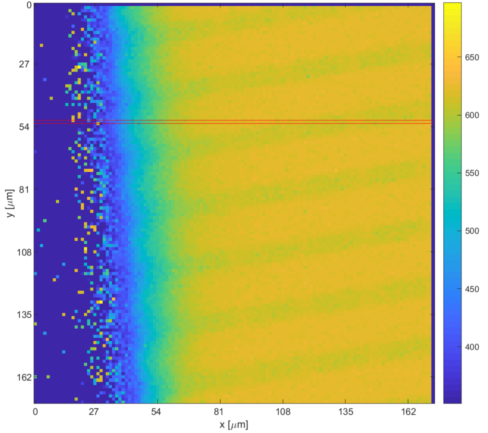
Mean Energy Map for acq. 447, Sensor thickness = 300 μm, Pix25 with V_{bias} = 150 V



Mean Energy Map for acq. 448, Sensor thickness = 300 μm, Pix25 with V_{bias} = 160 V

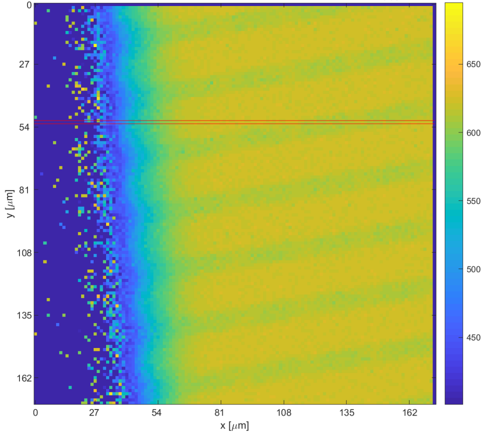


Mean Energy Map for acq. 449, Sensor thickness = 300 μm, Pix25 with V_{bias} = 170 V

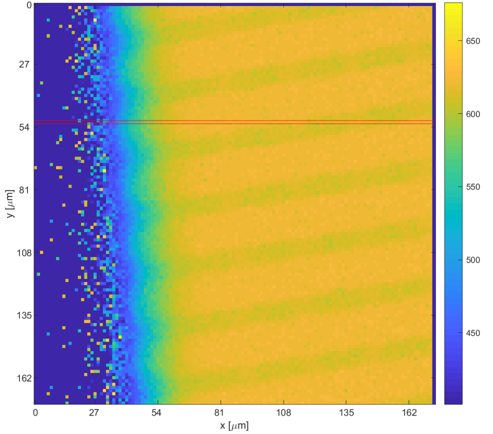


Bias Voltage

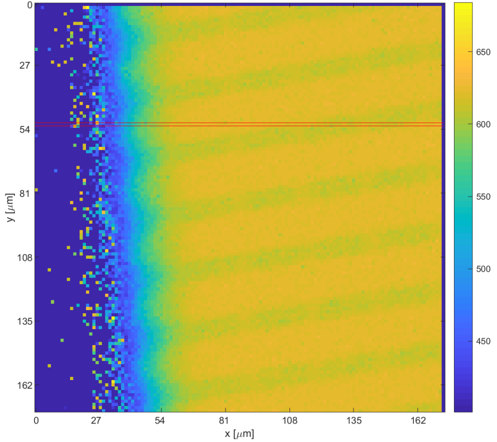
Mean Energy Map for acq. 450, Sensor thickness = 300 μm, Pix25 with V_{bias} = 180 V



Mean Energy Map for acq. 451, Sensor thickness = 300 μm, Pix25 with V_{bias} = 190 V



Mean Energy Map for acq. 452, Sensor thickness = 300 μm, Pix25 with V_{bias} = 200 V



Considering the 25 µm pixel pitch on the 300 µm thick sensor, by increasing the bias voltage these characteristics can be noticed:

- An improvement on the edge's electric field
- An increased charge collection uniformity

SETUP

Power supply units:

- HAMEG HMP2030 Low Voltage PSU
- NHQ 202M HV module

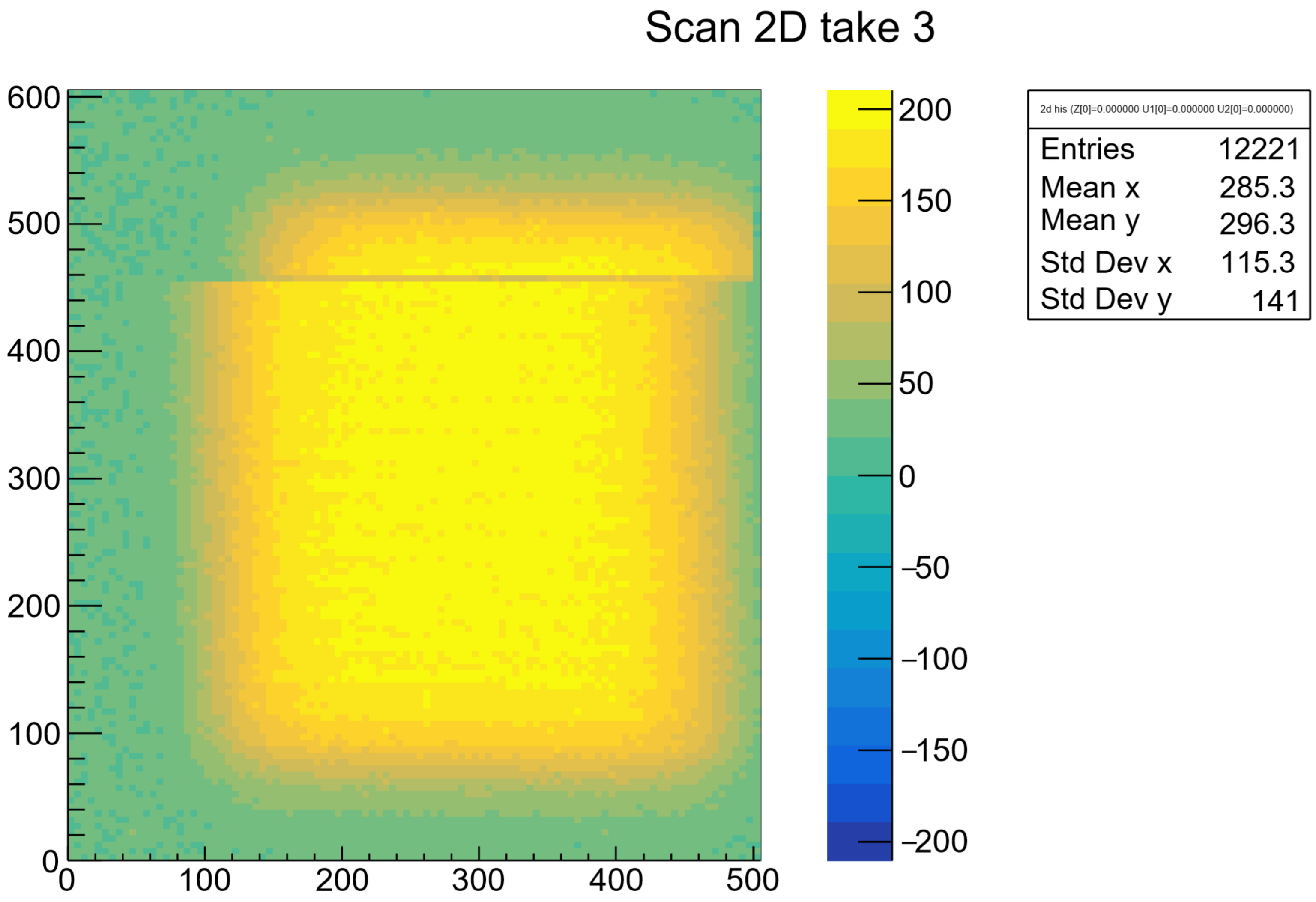
Readout electronics chain:

- ORTEC 142 Pre-Amplifier
- ORTEC 570 Shaper
- CANBERRA 8075 ADC

Software:

- Control SW *Spector*
- MATLAB

PREVIOUS SCAN RESULT



2d his (Z[0]=0.000000 U1[0]=0.000000 U2[0]=0.000000)

Entries	12221
Mean x	285.3
Mean y	296.3
Std Dev x	115.3
Std Dev y	141

REMEMBER:

- 25 µm PIXELS
- thickness = 300 µm
- 400 x 450 µm^2 region
- 30 µm LASER spot
- LASER att. = 40 % (1 MIP = 48 %)
- Step = 5 µm